Universitat Politècnica de València

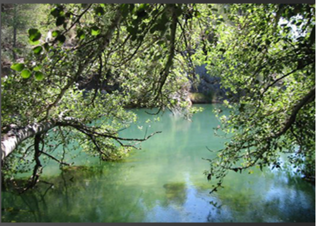
PhD Thesis

Riparian vegetation patterns according to hydrogeomorphological factors at different spatial and temporal scales in Mediterranean rivers

Presented by: Virginia Garófano Gómez
Supervisor: Francisco Martínez Capel

Valencia (Spain), March 2013



Universitat Politècnica de València

Departament d'Enginyeria Hidràulica i Medi Ambient
PhD Program in Water and Environmental Engineering

PhD Thesis

RIPARIAN VEGETATION PATTERNS ACCORDING TO HYDROGEOMORPHOLOGICAL FACTORS AT DIFFERENT SPATIAL AND TEMPORAL SCALES IN MEDITERRANEAN RIVERS

Presented by:
Virginia Garófano Gómez

Supervisor:
Francisco Martínez Capel

Valencia (Spain), March, 2013

"Nuestras vidas son los ríos;

nuestros ríos son la vida"

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This PhD thesis would not have been possible without the help of so many people in many different ways.

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ABSTRACT

The riparian corridors in semi-arid Mediterranean environments are ecosystems of high biodiversity and complexity. A variety of natural disturbances create a spatial and temporal environmental mosaic with few parallels in other systems. However, they are threatened because of high levels of human intervention. River damming (and related flow manipulation) is considered as one of the most prominent human impacts on riparian corridors. The aim of this thesis was to analyse the riparian ecosystem by covering different spatial and temporal scales and focusing on the factors that influence their vegetation distribution, structure, composition, quality and dynamics in free-flowing and hydrologically altered reaches of Mediterranean rivers. It focuses specifically on the Júcar River Basin District (Eastern Spain).

The specific objectives of this thesis were: **A**) Determining the positional patterns of woody riparian species in the transversal floodplain gradient and defining groups of species with similar response to the physical habitat conditions; **B**) Comparing the response of coincident species between free-flowing and hydrologically altered sites; **C**) Defining response curves and hydrological guilds of species in free-flowing rivers; **D**) Determining the main factors driving the riparian and instream habitat quality and longitudinal patterns of the floristic composition and instream habitat characteristics in a hydrologically altered river segment; **E**) Describing the spatiotemporal changes in riparian structure and complexity, and temporal changes in the stream flow regime within the riparian corridor of a hydrologically altered river reach.

The aforementioned objectives were tackled with different methodologies that involved the combination of different data sources and an important effort in field data collection in different study locations of the Cabriel, Mijares and Serpis rivers. To meet objectives **A** and **B**, soil sampling and geo-referenced vegetation survey by cross-sectional transects was conducted in two free-flowing and three regulated sites. Data analyses were performed with multivariate and robust statistics. To meet objective **C**, the aforementioned geo-referenced survey (along with a dendrochronological sampling) was

coupled with a hydraulic model in the two free-flowing sites in order to obtain the time series of water elevations at which every single plant had been exposed during its lifetime. The species response and their possible aggregation into hydrological guilds was compared through robust statistics in terms of inundation duration, inundation duration during the growth period, continuous inundation duration, inundation frequency and plant elevation above base flow. To meet objective **D**, the regulated section (Beniarrés dam – Sea; 40 km) of the Serpis River was divided into segments. In each one, a flora inventory was conducted and hydromorphological indices were applied. Different multivariate statistics allowed the grouping of sites according to their floristic composition and instream habitat characteristics. The main factors controlling the spatial patterns of the floristic composition, instream habitat characteristics, riparian habitat quality and instream habitat heterogeneity were discussed. To meet objective **E**, historical flow series and their human manipulation were combined with historical aerial images (depicting changes in land cover), ground observations of the species – age composition and morphology of the riparian corridor of the Mijares River over the last 60 years. A variety of landscape metrics and flow indices were extracted to identify and summarize spatio-temporal changes in the riparian structure and in the stream flow regime.

The transversal-scale study helped to understand the riparian zonation of each site in terms of morphology and soil characteristics, revealing that flow alteration may result into changes of the positional patterns of woody riparian species. Three hydrological guilds were defined, 'highly tolerant to inundation', 'intermediate tolerant' and 'transitional between floodplain and terrestrial'. The longitudinal-scale study suggested that the response of the vegetation to a hydrologic change is highly dependent on the local geomorphology. The main factors driving hydromorphological and floristic patterns were artificial and highly variable flow regimes (identified in sites with the worst riparian and instream quality), the presence of lateral structures in the river channel and geomorphological characteristics. As major effects after flow regulation, the spatiotemporal-scale study revealed an increase in the cover and density of woody vegetation, a shift in species composition and a decrease in bare sediment areas (essential for recruitment of riparian pioneer species) coupled with a synchronous reduction in the complexity of the riparian corridor. These changes can be related to the decrease in the magnitude and variability of river flows over the last six decades. Only a better understanding of the ecohydrological processes and the implications of hydrological alteration can support the effective management and integration of Mediterranean riparian systems into water management decisions.

RESUMEN

Los corredores riparios en ambientes semiáridos mediterráneos son ecosistemas de gran biodiversidad y complejidad. En ellos confluyen una gran variedad de perturbaciones naturales capaces de crear un mosaico espacial y temporal con pocos paralelos en otros ecosistemas. Sin embargo, a pesar de su valor, los ecosistemas riparios están amenazados debido a los altos niveles de intervención humana. La construcción de presas (y la consecuente manipulación del caudal) está considerada como la perturbación humana más importante que se cierne sobre ellos. Esta tesis ha tenido como objetivo analizar el ecosistema ripario, abarcando diferentes escalas espaciales y temporales, y centrándose en los factores que influyen en la distribución, estructura, composición, calidad y dinámica de su vegetación, tanto en tramos naturales como hidrológicamente alterados de ríos mediterráneos, concretamente de la Demarcación Hidrográfica del Júcar (Este de España).

Para lograr este objetivo, se han hecho los siguientes aportes a la investigación: **A**) Determinar los patrones de distribución de especies leñosas riparias en el gradiente transversal de la ribera y definir grupos de especies con respuesta similar a las condiciones físicas del hábitat; **B**) Comparar la respuesta de dichas especies en tramos naturales y alterados hidrológicamente; **C**) Definir curvas de respuesta y gremios hidrológicos de especies en tramos con régimen natural; **D**) Establecer los principales factores que determinan la calidad del hábitat ripario y fluvial y los patrones longitudinales de la composición florística, así como de las características del hábitat fluvial en un segmento hidrológicamente alterado; **E**) Describir los cambios espacio-temporales en la estructura y complejidad de la vegetación, y los cambios temporales en el régimen de caudales del corredor ripario de un tramo hidrológicamente alterado.

Los objetivos anteriores fueron abordados con diferentes metodologías que implicaron la combinación de diversas fuentes de información y un esfuerzo importante en la toma de datos en varios lugares de estudio de los ríos Cabriel, Mijares y Serpis. Para cumplir con los objetivos **A** y **B**, se llevaron a cabo un muestreo de suelos y un muestreo georreferenciado de vegetación a través de

transectos transversales al cauce en dos tramos naturales y tres regulados. Los datos fueron analizados con estadística robusta y multivariante. Para cumplir el objetivo **C**, el muestreo georreferenciado anterior (junto con un muestreo dendrocronológico) fue acoplado con un modelo hidráulico en los dos tramos naturales, con el fin de obtener la serie temporal de cotas del agua a la que habían estado expuestas cada una de las plantas durante su vida. La respuesta de las especies y su posible agregación en gremios hidrológicos fue comparada mediante estadística robusta en relación a la duración de la inundación, duración de la inundación durante el período de crecimiento, duración continua de la inundación, frecuencia de inundación y elevación de la planta respecto al caudal base. Para lograr el objetivo **D**, toda la sección regulada del río Serpis (desde la presa Beniarrés - hasta la desembocadura; 40 km) se dividió en segmentos. En cada uno de ellos se llevó a cabo un inventario de flora y se aplicaron índices hidromorfológicos. Los segmentos fueron agrupados de acuerdo a su composición florística y características del hábitat fluvial utilizando diferentes técnicas de estadística multivariante. Finalmente se discutieron los factores principales que controlan los patrones espaciales de la composición florística, las características del hábitat fluvial, la calidad del hábitat ribereño y la heterogeneidad del hábitat fluvial. Para alcanzar el objetivo **E**, se combinaron series históricas de caudales y su manipulación humana con imágenes aéreas históricas (reveladoras de cambios en la cubierta vegetal) y observaciones de campo de la distribución de edades de la vegetación y morfología del corredor ripario del río Mijares en los últimos 60 años. De esta información, se extrajeron métricas del paisaje e índices hidrológicos para identificar y resumir los cambios espacio-temporales en la estructura de la ribera y en el régimen de caudales.

El estudio a escala transversal nos ayudó a comprender en cada uno de los tramos la zonación de las especies leñosas riparias en función de la morfología y características del suelo, revelando que la alteración del caudal puede influir en la modificación de los patrones posicionales de las especies. Se definieron tres gremios hidrológicos: “altamente tolerante a la inundación”, “tolerante intermedio” y “de transición entre ripario y terrestre”. El estudio a escala longitudinal sugirió que la respuesta de la vegetación a un cambio hidrológico es altamente dependiente de la geomorfología local. Se constató que los factores principales que determinan los patrones hidromorfológicos y florísticos son un régimen de caudales artificial y altamente variable (identificado en los segmentos con peor calidad del hábitat ripario y fluvial), la presencia de estructuras laterales en el cauce y las características geomorfológicas. Como efectos importantes de la regulación del caudal a largo plazo, el estudio a escala espacio-temporal reveló un aumento en la cobertura y densidad de la vegetación leñosa, una deriva en la composición de especies y una disminución en las áreas de sedimento desnudo (esencial para el reclutamiento de las especies riparias pioneras), junto con una reducción sincrónica en la complejidad de la ribera. Estos cambios estarían relacionados con la disminución de la magnitud y variabilidad de los caudales en las últimas seis décadas. Solo una mejor comprensión de los procesos ecohidrológicos y de las implicaciones de la alteración hidrológica sobre los ecosistemas riparios mediterráneos podrá apoyar la integración eficaz de estos sistemas en las decisiones de gestión del agua.

RESUM

Els corredors riparis en ambients semiàrids mediterranis són ecosistemes de gran biodiversitat i complexitat. Hi conflueixen una gran varietat de pertorbacions naturals capaces de crear un mosaic espacial i temporal amb pocs paral·lels en altres ecosistemes. No obstant això, tot i el seu valor, els ecosistemes riparis estan amenaçats a causa de alts nivells d'intervenció humana. La construcció de preses (i la consegüent manipulació del cabal) està considerada com la pertorbació humana més important que plana sobre ells. L'objectiu principal d'aquesta tesi ha estat analitzar l'ecosistema ripari, abastant diferents escales espacials i temporals, centrant-s'hi en els factors que influeixen en la distribució, estructura, composició, qualitat i dinàmica de la seua vegetació, tant en trams naturals com hidrològicament alterats de rius mediterranis, concretament de la Demarcació Hidrogràfica del Xúquer (est d'Espanya).

Per a aconseguir aquest objectiu, s'han fet les següents aportacions a la recerca: **A**) Determinar els patrons de localització d'espècies llenyoses ripàries en el gradient transversal de la ribera i definir grups d'espècies amb resposta similar a les condicions físiques de l'hàbitat; **B**) Comparar la resposta de les espècies en trams naturals i alterats hidrològicament, **C**) Definir corbes de resposta i gremis hidrològics d'espècies en trams amb règim natural; **D**) Establir els principals factors que determinen la qualitat de l'hàbitat ripari i fluvial i els patrons longitudinals de la composició florística alhora que les característiques de l'hàbitat fluvial en un segment hidrològicament alterat; **E**) Descriure els canvis espaciotemporals en l'estructura i complexitat de la vegetació, pel que fa als canvis temporals en el règim de cabals del corredor ripari d'un tram hidrològicament alterat.

Els objectius anteriors van ser abordats amb diferents metodologies que van implicar la combinació de diverses fonts de dades i un esforç important de presa de dades en diverses localitzacions dels rius Cabriol, Millars i Serpis. Per a acomplir amb els objectius **A** i **B**, es van dur a terme un mostreig de sòls i un mostreig georeferenciat de vegetació mitjançant transectes transversals a la llera

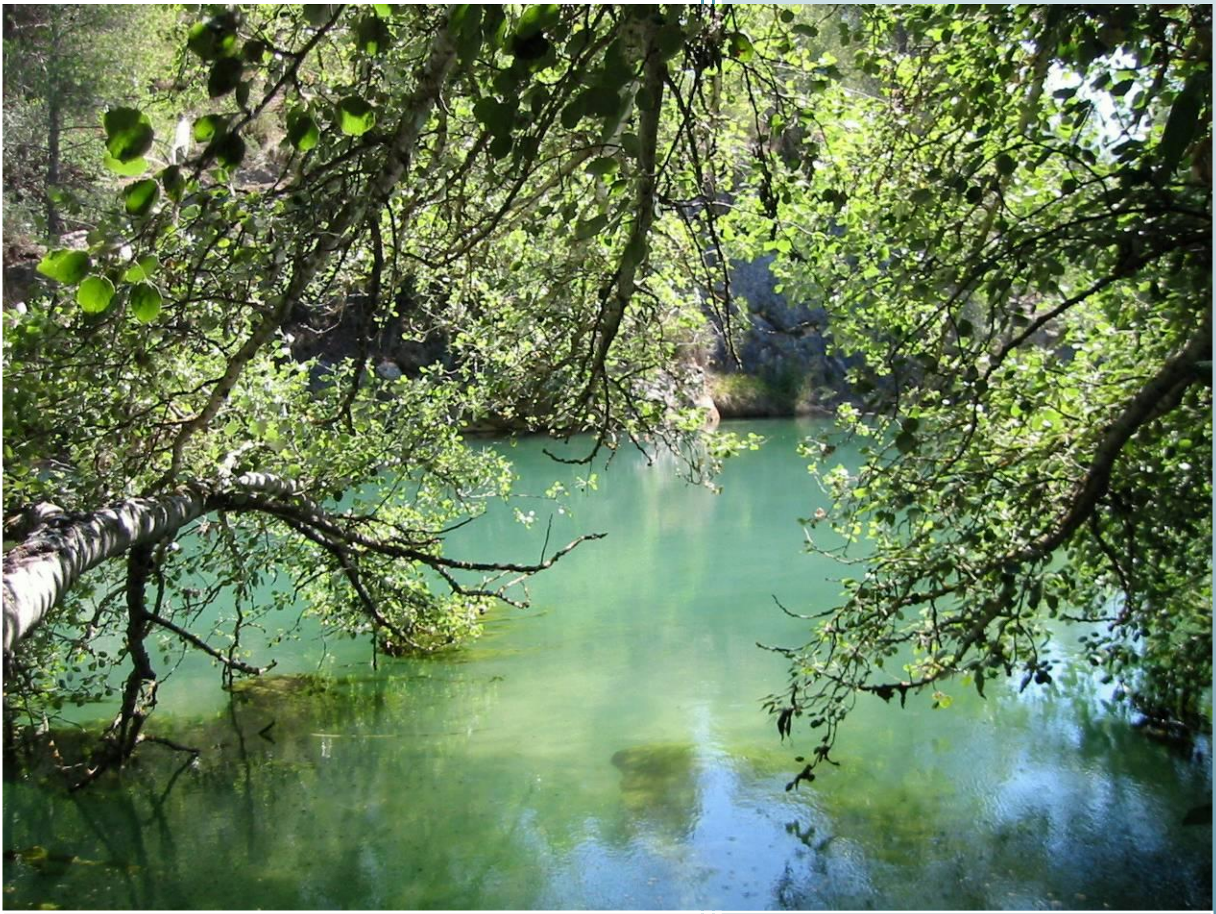
en dos trams naturals i tres regulats. Les dades van ser analitzades amb estadística robusta i multivariant. Per a acomplir amb l'objectiu **C**, el mostreig georeferenciat anterior (juntament amb un mostreig dendrocronològic) va ser acoblat amb un model hidràulic en els dos trams naturals, amb la finalitat d'obtenir la sèrie temporal de cotes de l'aigua a la qual havia estat exposada cadascuna de les plantes al llarg de la seua vida. La resposta de les espècies i la seua possible agregació en gremis hidrològics va ser comparada mitjançant estadística robusta en relació a la durada de la inundació, durada de la inundació durant el període de creixement, durada contínua de la inundació, freqüència d'inundació i elevació de la planta respecte del cabal base. Per a acomplir amb l'objectiu **D**, tota la secció regulada del riu Serpis (des de la presa Beniarrés fins a la desembocadura; 40 km) es va dividir en segments. En cadascun d'ells es va dur a terme un inventari de flora i es van aplicar índexs hidromorfològics. Els segments van ser agrupats d'acord a la seua composició florística i característiques de l'hàbitat fluvial utilitzant diferents tècniques d'estadística multivariant. Finalment es van discutir els factors principals que controlen els patrons espacials de la composició florística, les característiques de l'hàbitat fluvial, la qualitat de l'hàbitat riberenc i l'heterogeneïtat de l'hàbitat fluvial. Per tal d'assolir l'objectiu **E** es van combinar sèries històriques de cabals i la seua manipulació humana amb imatges aèries històriques (reveladores de canvis en la coberta vegetal), observacions de camp de la distribució d'edats de la vegetació i morfologia del corredor ripari del riu Millars en els últims 60 anys. D'aquesta informació, es van extreure mètriques del paisatge i índexs hidrològics per identificar i resumir els canvis espaciotemporals en l'estructura de la ribera i en el règim de cabals.

L'estudi a escala transversal ens va ajudar a comprendre a cadascun del trams la zonació de les espècies llenyoses ripàries en funció de la morfologia i característiques del sòl, revelant que l'alteració del cabal pot influir en la modificació dels patrons de localització de les espècies. Es van definir tres gremis hidrològics: “altament tolerant a la inundació”, “tolerant intermedi” i “de transició entre ripari i terrestre”. L'estudi a escala longitudinal va suggerir que la resposta de la vegetació a un canvi hidrològic és altament dependent de

la geomorfologia local. Es constatà que els factors principals que determinaven els patrons hidromorfològics i florístics són un règim de cabals artificial i altament variable (observat als segments amb pitjor qualitat de l'hàbitat ripari i fluvial), a més de la presència d'estructures laterals a la llera i determinades característiques geomorfològiques. Com efectes importants de la regulació del cabal a llarg termini, l'estudi a escala espaciotemporal va revelar un augment en la cobertura i densitat de la vegetació llenyosa, una deriva en la composició d'espècies i una disminució en les àrees de sediment al descobert (essencial per al reclutament de les espècies ripàries pioneres), juntament amb una reducció sincrònica en la complexitat de la ribera. Aquests canvis estarien relacionats amb la disminució de la magnitud i variabilitat dels cabals a les últimes sis dècades. Només una millor comprensió dels processos ecohidrológicos i de les implicacions de l'alteració hidrològica sobre els ecosistemes riparis mediterranis podrà donar suport a la gestió i integració eficaç d'aquests sistemes en les decisions de gestió de l'aigua.

GENERAL INDEX

Chapter 1



General introduction

1 GENERAL INTRODUCTION

1.1 OVERVIEW

Riparian ecosystems are some of the most dynamic and complex biophysical habitats on the terrestrial portion of the planet (Malanson, 1993; Naiman *et al.*, 1998). A variety of natural disturbances creates a spatial and temporal environmental mosaic with few parallels in other systems (Naiman and Décamps, 1997). Furthermore, their topographical, sedimentological and hydrological heterogeneity make them one of the richest ecosystems in terms of species diversity (Naiman *et al.*, 1993). This fact is specially relevant in the riparian zones of Mediterranean-climate regions (Santos, 2010), where they support a dense and productive closed-canopy forest ecosystem relative to the surrounding landscape, which is typically a matrix of xeric woodlands, shrub and grassland communities (Stella *et al.*, 2012). In addition to their high natural biodiversity, riparian zones provide numerous ecosystem functions and services related to water quality, microclimate, structural habitat for wildlife and fish, an energy base for the food web, and bank stability, among others (Naiman *et al.*, 2005). Despite their value, riparian zones have been declared as one of the most threatened ecosystems of the planet (Millennium Ecosystem Assessment, 2005). In certain areas, according to the Spanish Ministry of Agriculture, Food and Environment, riparian forests are almost the only remaining natural ecosystems.

The multiple functions of the riparian vegetation and its role in the fluvial ecosystem, as well as a quality indicator, have led scientists to go deeply into their knowledge to preserve and enhance our rivers, in accordance with the European directives on water management and environmental conservation. In this sense, this thesis is intended to analyse the riparian ecosystem covering different spatial and temporal scales, and focusing on the factors that influence their distribution, structure, composition and dynamics in the Mediterranean context. Due to, as it will be further explained, each chapter has been conceived with a different approach, each one is contextualized independently with its own background and state of the art.

1.2 OBJECTIVES AND STRUCTURE OF THE THESIS

The thesis was aimed to improve our knowledge of the relationships between riparian vegetation and hydrogeomorphological factors through a range of different spatial and temporal scales in western Mediterranean rivers, specifically within the Júcar River Basin District (Eastern Spain).

To achieve this, we made the following specific research contributions:

A. To determine the positional patterns of the different woody riparian species in the transversal floodplain gradient and define groups of species with similar response to the physical habitat conditions (river morphology and soil properties) in different study sites.

B. To compare the response to the physical habitat conditions of coincident woody riparian species between free-flowing and hydrologically altered study sites.

C. To define guilds of woody riparian species according to the hydrological response in rivers with a natural flow regime.

D. To determine the main factors driving the longitudinal patterns of the floristic composition and instream habitat characteristics, as well as the riparian and instream habitat quality in a hydrologically altered river segment.

E. To describe the spatiotemporal changes in riparian structure and complexity and temporal changes in the driving flow processes within the riparian corridor of a hydrologically altered river reach.

To achieve these goals, the thesis was structured in several chapters, which mimic the structure of a scientific article, i.e., in each one, several specific objectives are contextualized, the specific study area and methods are described and results are presented and discussed. The contents of each chapter are summarized below.

- **Chapter 2.** *Distribution patterns of woody riparian species in Mediterranean rivers. Comparison of regulated and unregulated sites.* The positional patterns of the main woody riparian species in the lateral gradient of the floodplain were analysed in terms of the physical conditions: river morphology (distance and elevation to/above thalweg) and soil characteristics (texture, organic matter and moisture content). This transversal-scale study was conducted by cross-sections in five river reaches (two of them free-flowing, named as Cabriel-Rabo del Batán and Mijares-Terde, and three of them regulated, named as Mijares-Cirat, Mijares-Tormo and Serpis-Lorcha). Groups of species with similar response to the environmental conditions were defined; besides, the response of coincident species in free-flowing and regulated sites was compared. Part of the information presented in this chapter has been presented as a full paper in the *7th International Symposium on Ecohydraulics* held in Concepción, Chile (Garófano-Gómez *et al.*, 2009b) and in the *3rd SCARCE International Conference*, held in Valencia, Spain (Garófano-Gómez *et al.*, 2012), where it was recognized with the second price of the student poster awards.

- **Chapter 3**. *Response curves and hydrological guilds of woody riparian species, oriented to water management in Mediterranean rivers.* The same information by transects from the two free-flowing reaches presented in the previous chapter, along with drendrochronological estimations and flow time series, was used to define guilds and curves of hydrological response for key woody riparian species. A previous version of the results presented here was presented as a full paper in the *8th International Symposium on Ecohydraulics*, held in Seoul, South Korea (Garófano-Gómez *et al.*, 2010).

- **Chapter 4**. *Hydromorphological and floristic patterns along a regulated Mediterranean river: The Serpis River.* In this chapter, a longitudinal-scale study conducted by plots within study reaches is presented, whose goal was to determine the main factors driving the spatial patterns of the floristic composition, riparian quality, instream habitat characteristics and heterogeneity on a hydrologically altered segment of the Serpis River. Part of the results of this research are included in the book *Les riberes del Serpis. Gestió de l'aigua per a la seua conservació*, published by the Centre d'Estudis i Investigacions Comarcals Alfons El Vell (Garófano-Gómez *et al.*, 2009a) and in an article in the scientific journal *Limnetica* (Garófano-Gómez *et al.*, 2011b).

- **Chapter 5**. *Six decades of changes in the riparian corridor of a Mediterranean River: A synthetic analysis based on historical data sources.* This chapter presents a spatiotemporal-scale study conducted at species and patch level, in a reach of the middle course of the Mijares River, in order to interpret the long-term changes in the structure and complexity of its riparian corridor due to flow regulation. Previous results of this research were presented in the *IVth ECRR International Conference on River Restoration*, held in Venice, Italy (Garófano-Gómez *et al.*, 2008) and in the *EUROMECH Colloquium 523. Ecohydraulics: linkages between hydraulics, morphodynamics and ecological processes in rivers,* held in Clermont-Ferrand, France (Garófano-Gómez *et al.*, 2011a), and later on in an article in the scientific journal *Ecohydrology* (Garófano-Gómez *et al.*, *in press*).

Finally, in **Chapter 6**, the main conclusions derived from this thesis are presented and some future research guidelines are explained.

1.3 STUDY AREA: THE JÚCAR RIVER BASIN DISTRICT

This thesis has been developed in different Mediterranean rivers from the Júcar River Basin District (RBD), which is located in Eastern Spain (**Figure 1.1 a, b**), between latitudes 38° and 40° north and has a total area about 43000 km^2. In general, the RBD presents strong gradients from NW to SE in terms of population density, elevation, climate, etc. Due to this particular conditions, the Júcar RBD was chosen as a European pilot basin by the Spanish Ministry of Environment in 2002 to test the Guidance Documents of the Water Framework Directive 2000/60/EC (European Commission, 2000).

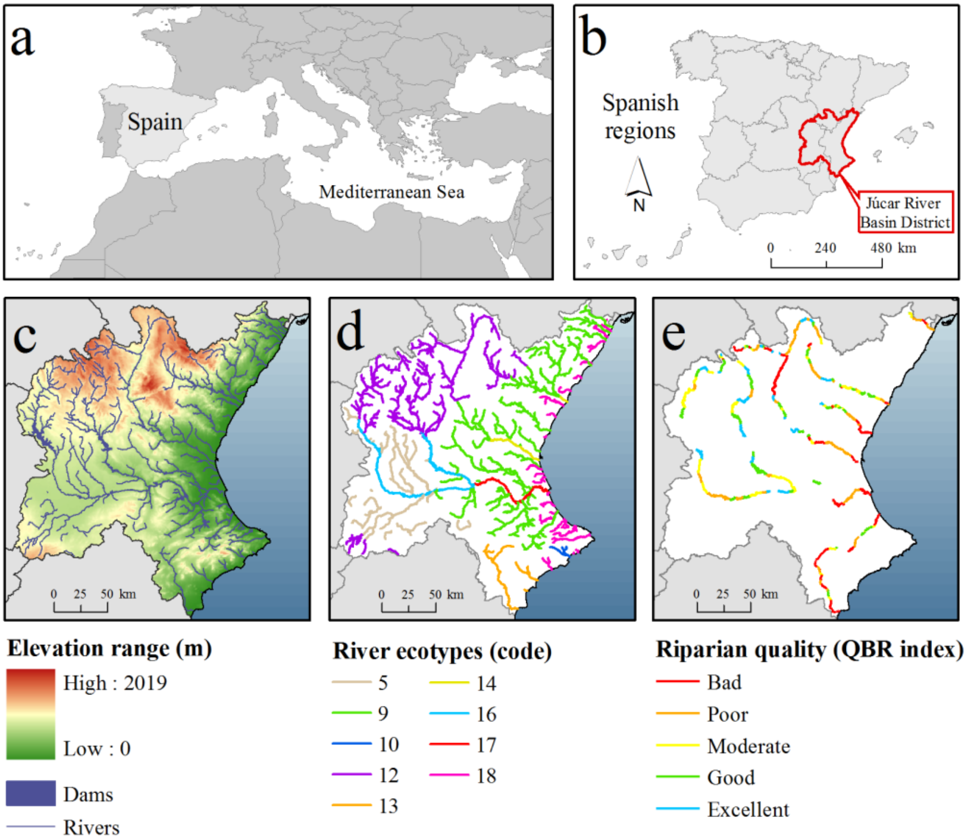


Figure 1.1. *General characteristics of the Júcar River Basin District (Eastern Spain) within the Mediterranean context (a and b). It has a wide elevation range, exceeding 2000 m above sea level in some areas and its coastal plain is over 400 km long and 40 km broad in its widest section (c). Its river network has been classified into nine different ecotypes (d). In general, its riparian quality is worst in the coastal streams than in its mountain streams (e).*

From the 17 Spanish regions (also known as Autonomous Communities), the Júcar RBD encompasses part of four of them: Valencian Community (49.6 %

of total area of the Júcar RBD), Castilla-La Mancha (36.6 %), Aragón (13.2 %) and Cataluña (0.6 %). However, in terms of population within the RBD, more than 90 % of its inhabitants live in the Valencian Community, percentage that increases when considering the tourism. As mentioned before, there is a strong population density gradient, with high values in the Mediterranean coast and very low in the mountainous areas of the western part of the RBD.

Three major geomorphic features can be distinguished within the Júcar RBD (**Figure 1.1 c**). First, the coastal zone, which is composed by depositional coastal plains. The most important are Oropesa-Torreblanca, Castellón-Sagunto, Valencia-La Ribera, Favara-Gandía-Denia. Second, the inland, which comprises a high continental plateau (average height of 650 m), known as 'Llanura Manchega'. And third, the mountainous area, which rises above 1000 m altitude. The highest peak, known as Peñarroya, has an altitude of 2024 m above sea level. These three different zones represent 33 %, 42 % and 25 % of the total area of the RBD, respectively.

In general, the Júcar RBD can be defined as a semi-arid zone as a whole. It has an irregular hydrology very characteristic of Mediterranean basins. Droughts and floods episodes are highly common within its territory, even during the same year. It enjoys a Mediterranean climate with hot-dry summers and mild winters (Estrela *et al.*, 2004). Average annual temperatures range from 14 to 16.5 ºC. The average annual rainfall is 500 mm (period: 1940-2003); however, there is large spatial and temporal variability. Therefore, due to the geographical and geomorphological characteristics, there are some notable differences among Northern and Southern, Eastern and Western parts. These differences increase climatic effects such as thermal inversions that produce catastrophic floods along the coast. In this sense, in October and November, precipitation events may occur with great intensity and short duration. Such phenomena are called 'medicanes' (Mediterranean-hurricanes) and are popularly known in Spanish as '*gota fría*'.

The Júcar RBD encompasses 9 river basins (from north to south: Cenia, Mijares, Palancia, Turia, Júcar, Serpis, Marina Alta, Marina Baja and Vinalopó). Júcar, Turia and Mijares together provide 80 % of the total surface water resources. Among them, the Júcar River is the largest, with a mean supply equivalent to 55 % of the total available resource. On the other hand, groundwater represents 73 % of total water consumption within the Júcar RBD.

The river network of the Júcar RBD has been classified into nine different river ecotypes (CHJ, 2005a) by the Spanish Ministry of Environment with the collaboration of a Spanish Research Center, so-called Centro de Estudios y Experimentación de Obras Públicas (CEDEX, 2004). This means that the water bodies with similar characteristics have been classified into groups with an ecological meaning, in relation to variables such as mean annual discharge, mean annual temperature, altitude, conductivity, mean slope of the watershed and Strahler stream order (**Figure 1.1 d**). These ecotypes are (code in brackets): *rivers of La Mancha (5), mineralised rivers in middle and low Mediterranean mountain (9), karstic Mediterranean rivers (10), rivers in calcareous Mediterranean mountain (12), highly mineralised Mediterranean rivers (13), low altitude Mediterranean main stems (14), mineralised continental-Mediterranean main stems (16), large Mediterranean main stems (17), and coastal Mediterranean rivers (18).*

Surface water bodies include rivers, lakes, transitional and coastal waters, and heavily modified and artificial water bodies; only 27 % of all water bodies are considered as pristine water reaches (Estrela *et al.*, 2004). Approximately, 22 % of the total surface of the Júcar RBD is covered by Natura 2000 sites. These areas belong to the Sites of Community Importance (SCI) and the Special Protection Areas for birds (SPA). A large proportion of protected areas are located in the mountainous areas and in main watercourses.

According to the Corine Land Cover 2000, within the limits of the Júcar RBD, the dominant land use is forest and semi natural areas, which cover 50 % of the territory. Agricultural non-irrigated areas cover 36 % and agricultural irrigated areas 10 %. Urban and industrial zones cover 3 % of the territory and less than 1 % is represented by wetlands and water surfaces (CHJ, 2005a).

Most of the rivers of the RBD have the source in the highest peaks and finish in the Mediterranean Sea, acting as ecological corridors connecting high mountain areas with plains in the middle river courses. Frequently, these rivers run across narrow mountain valleys with hardly any or very small portion of floodplains. According to the climate, lithology and geomorphology, different kinds of associated riverine vegetation can be found. The riparian forest is the maximum expression of its biological diversity. The North with a more humid climate holds permanent water courses with willows, ashes, poplars and elms. The drier South presents riversides with no permanent fluvial regime; therefore the vegetation is dominated by saltcedar and oleander.

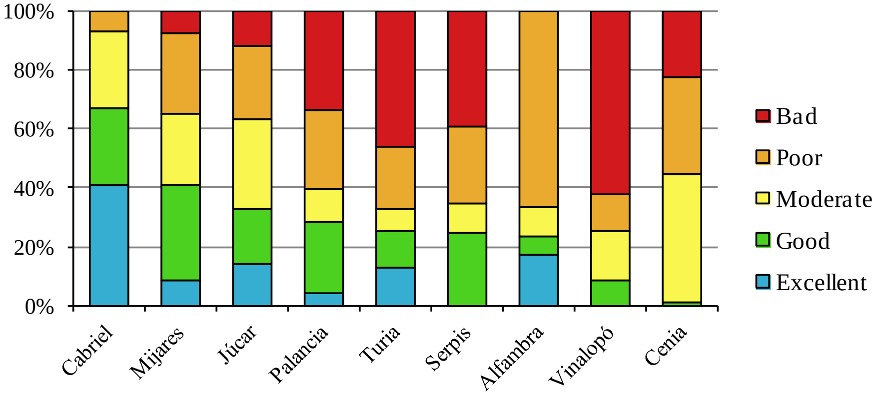


Figure 1.2. *Distribution of the different classes of riparian habitat quality assed by the QBR index (Munné et al., 2003) in the main permanent river courses of the Júcar River Basin District. Information extracted from Aguilella et al. (2005).*

In terms of riparian quality, Aguilella *et al.* (2005) evaluated almost 1500 km of the main permanent river courses of the Júcar RBD, through the Riparian Habitat Quality Index – QBR (Munné *et al.*, 1998; Munné *et al.*, 2003). They concluded that the Cabriel River is the river with the best conservation status within the entire RBD, having 67 % of its entire length classified as good-excellent (**Figure 1.2**), whereas the rest of the rivers present lower values (Mijares: 41 %; Júcar: 33 %; Palancia: 28 %; Turia: 26 %; Serpis: 25 %; Alfambra: 23 %; Vinalopó: 9 %; Cenia: 1 %).

Flow regulation analysis carried out by the Júcar River Basin Authority (Estrela *et al.*, 2004), reveals that major rivers (the Júcar as well as its main tributary the Cabriel, the Turia and the Mijares River), are strongly regulated from the upper/middle river course to the mouth. The upper parts of rivers and short watercourses are less affected by regulation structures, and therefore show the highest ecological value, as revealed by the QBR index.

As a result, the Júcar RBD constitutes an excellent study area for research on hydrology-ecology relationships in Mediterranean riparian areas. Not only because its high variability in natural conditions and remaining areas of remarkable riparian quality but also because its high regulation allows the analysis of its consequences on riparian ecosystems.

Chapter 2

Distribution patterns of woody riparian species in Mediterranean rivers. Comparison of regulated and unregulated sites

2 DISTRIBUTION PATTERNS OF WOODY RIPARIAN SPECIES IN MEDITERRANEAN RIVERS. COMPARISON OF REGULATED AND UNREGULATED SITES

2.1 ABSTRACT

The positional patterns of key woody riparian species were analysed in five study sites in the Júcar River Basin District (Eastern Spain) with the purpose of defining groups of species that respond similarly to the physical habitat conditions, in particular the river morphology (distance and elevation to/above thalweg) and soil characteristics (texture, organic matter and moisture content). In addition, the riparian vegetation composition and configuration in each site was described according to its richness, abundance, cover and density. A combination of robust and multivariate statistics were performed in order to analyze the joint variation of all variables and obtain groups of species with a similar response in a multivariate way. The results of this chapter have been divided into two sections, one for intra-site comparisons; and another for inter-site comparisons, where the differences between free-flowing and regulated sites are presented. Additionally, the response of the coincident species between both types of sites is compared. This transversal-scale study helped to understand the riparian zonation of each site in terms of morphology and soil characteristics, revealing that flow alteration may result into changes of the positional patterns of woody riparian species.

Keywords: Woody riparian vegetation, distribution patterns, thalweg, flow regime, Mediterranean rivers, multivariate interpretation.

2.2 INTRODUCTION

The knowledge of the riparian forests, regarding their distribution and composition has been largely expanded since the 1980's (Hupp and Osterkamp, 1985; Nilsson, 1986; Salo *et al.*, 1986; Slater *et al.*, 1987). Also the relations between riparian species and stream hydrology have been developed (Stromberg, 1993; Mahoney and Rood, 1998b; Shafroth *et al.*, 1998). Among such studies, some have used variables related to river morphology to explain the species distribution (Stromberg and Patten, 1996; Nakamura *et al.*, 1997; Van Coller *et al.*, 1997). Others have developed dynamic models to simulate growth and processes of succession/retrogression in the riparian ecosystem (Inamdar *et al.*, 1999; Glenz, 2005; Egger *et al.*, 2007; Benjankar *et al.*, 2011; García-Arias *et al.*, *in press*).

Fluvial disturbance and water stress factors vary along the lateral and longitudinal gradient of the river (Lite *et al.*, 2005) and therefore, are considered as two of the primary factors that influence spatial vegetation patterns (Malanson, 1993). Furthermore, the vegetation patterns are time-dependent and change with temporal variation in the primary factors (Nilsson *et al.*, 1994). Looking in detail laterally, i.e., along the transverse profile of the riparian zone, the intensity and frequency of flood disturbance typically diminish with increasing distance from (and above) the active channel. Along this same gradient, water stress may increase, due to generally larger ground-water depth.

In the context of semi-arid regions and especially in Mediterranean rivers, due to water scarcity, riparian vegetation patterns are highly influenced by factors such as flow regime, soil moisture and ground water availability (Tabacchi *et al.*, 1996). In addition, flood disturbance and water availability are interrelated and both vary greatly over time, for instance, wet years produce conditions of both low water stress and high disturbance and dry years result in high stress and low disturbance (Lite *et al.*, 2005). Besides, the intensity of the disturbance regime can influence plant species diversity at local scales (Ali *et al.*, 2000).

In the transverse profile, other important factors are the sedimentation rate and grain-size, which depend largely on the distance from the active channel system and ground elevation. Soil water is very important to the entire soil system as well, not only because it is necessary for plant growth, but because the nutrients required for plant growth are also present in the soil solution. Most of the important soil reactions (weathering, cation exchange, organic matter decomposition, fertilization) take place in the context of the soil solution. Thus, it is evident that not only the texture, but also the moisture status of a soil is a key property.

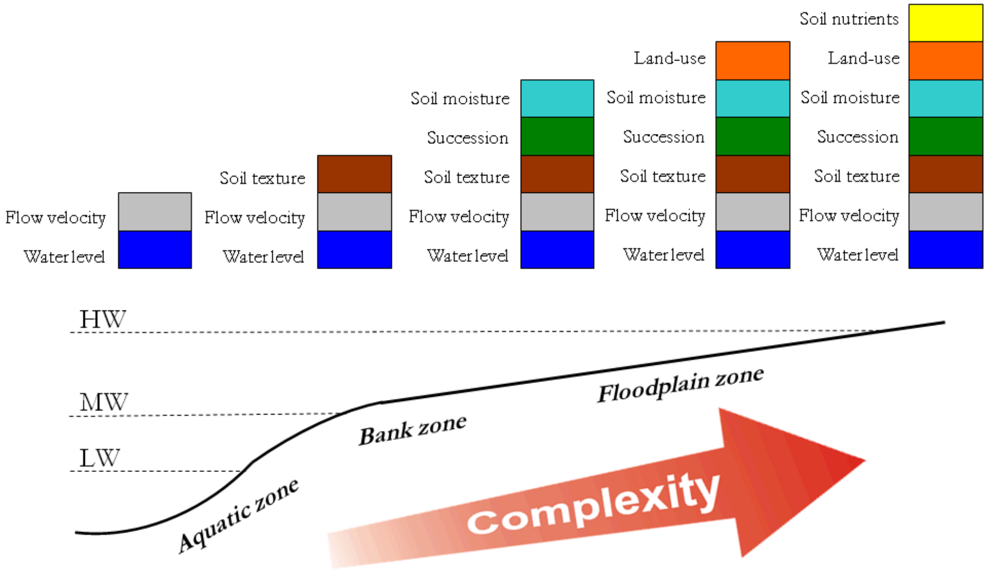


Figure 2.1. *Importance of different environmental variables as we move on the transverse gradient from the water's edge to the upland forest. Different water levels are indicated (low: LW, mean: MW; high: HW). Figure modified from Dr. Peter J. Horchler (pers. com.), Federal Institute of Hydrology (Germany).*

As can be seen in **Figure 2.1**, different environmental variables become important as we move farther in the transverse gradient. Firstly, water level and flow velocity are the key factors for plant establishment and development in the proximities of the aquatic zone (base flow or low water level conditions). In the bank zone, besides the previous factors, the soil texture plays its role. As the influence of the water level reduces and distance and elevation increase, the soil moisture becomes a limiting factor for plant development. Farther, in the floodplain zone, the vegetation succession via autogenic processes (internal mechanisms) is able to induce changes in the vegetation patterns with processes such as competition. Finally, in the transitional zone or ecotone between floodplain and upland, where only high flows of low recurrence take place, the land uses, increased soil depth profiles and nutrient pools become more important, promoting a more robust and well-developed vegetation.

Another important factor to take into consideration is the status of plant development. Herbaceous species may be more sensitive than trees and shrubs to disturbance, drought stress or geomorphic heterogeneity (Lyon and Sagers, 1998). According to Decocq (2002), tree and shrubs layers may respond to soil moisture and nutrient gradients, whereas the herbaceous communities may be most related to gradients of soil nutrients and light availability. In the same way, plants with different life-history strategies may respond to disturbances and stressors differently. Therefore, the definition of functional groups or guilds of plants with the same behaviour under specific environmental variables has been established as one of the keys in the development and validation of vegetation models (USDA-NRCS, 2002; Lite *et al.*, 2005; Merritt *et al.*, 2010; Bejarano *et al.*, 2012a). For this task, it is necessary to distinguish if different species are affected in the same way by certain environmental variables, and which species show significant differences. Other question arising is the applicability of the empirical results of a species (for example, in tolerance to inundation) in rivers with diverse physical conditions or the comparison of the performance of a certain species in rivers with different conditions. This is essential for the validation, in other rivers than the ones where the models were calibrated.

In consequence with these ideas, this study was developed in five study sites with different flow regimes and located in three rivers of the Júcar River Basin

District (Eastern Spain). The general objective of this study was to describe the riparian vegetation community of each one of the sites using different indicators and analyse the habitat suitability for their main species in terms of positional patterns (through two key morphological variables: distance and elevation to/above thalweg) and soil characteristics along the transverse gradient. More specifically, this study was developed in order to address the following questions:

A. How do woody riparian species distribute laterally across the floodplain in rivers with Mediterranean climate, in relation to distance and elevation to/above thalweg?; and in relation to the soil properties (texture, organic matter and moisture content)?

B. Are there significant differences in these environmental variables among the main riparian species in each study site? Is it possible to define groups of species with similar patterns?

C. Are there differences in the positional patterns and soil preferences of woody riparian species between rivers with different flow regime (regulated and unregulated)?

2.3 STUDY AREA

The study reaches (**Figure 2.2**, **Figure 2.3** and **Table 2.1**) were selected in permanent Mediterranean rivers of the Júcar River Basin District (East Spain). The selection was based on aerial photographs, field observation of plant diversity and riparian quality.

Two study reaches were selected in unregulated river segments in nearly-natural conditions. The first one known as 'Terde' was in the Mijares River, near the village of Sarrión (Teruel province); the second site, known as 'Rabo del Batán', was in the Cabriel River, near Carboneras de Guadazaón (Cuenca province). Additionally, three study reaches were selected in regulated river segments. Two of them were in the Mijares River, downstream of Arenós dam.

They were known as 'Cirat' and 'Tormo' (names that refer to the villages they are close to in Castellón province.). The third regulated site, named as 'Lorcha', was in the Serpis River, downstream of Beniarrés dam, near the limit between Alicante and Valencia provinces. The five sites have a notable scenic value and the impact of the agricultural activities is relatively low, except for the site Cirat, where the river channel and the floodplain are constrained by them.

Table 2.1. *Characteristics of the study reaches located in the Júcar River Basin District.*

	Cabriel R. Batán	**Mijares Terde**	**Mijares Cirat**	**Mijares Tormo**	**Serpis Lorcha**
Coordinate X (m)[1]	609259	689337	716429	720571	733362
Coordinate Y (m)[1]	4420615	4448933	4437573	4437676	4304165
Water body code[2]	18.21.01.04	10.03	10.06	10.07	21.06
Ecotype[3]	12	12	9	9	9
Strahler stream order	3	2	3	3	3
Mean elevation (m)	925	850	365	315	235
Site length (m)	910	530	180	150	240
Distance to dam upstream (Km) and year of construction	-	-	14.5 (1962-79)	21.7 (1968-79)	8.5 (1958)
Number of transects	20	20	9	9	11
Mean flow (m^3/s)[4]	6.191	0.858	1.535	0.870	1.083
Flow regime status	Unregulated		Regulated		

[1] European Datum 1950, UTM-Zone 30N.

[2] According to the Júcar River Basin Authority (CHJ, 2005a; CHJ, 2009b) the five water bodies have been classified as *natural.*

[3] Ecological typologies according to the Spanish Ministry of Environment (CEDEX, 2004; CHJ, 2009b): ecotype 12 '*rivers in calcareous Mediterranean mountain*' and 9 '*mineralised river in middle and low Mediterranean mountain*'.

[4] Values extracted from 'Proyecto Ribera' (Francés *et al.*, 2009)

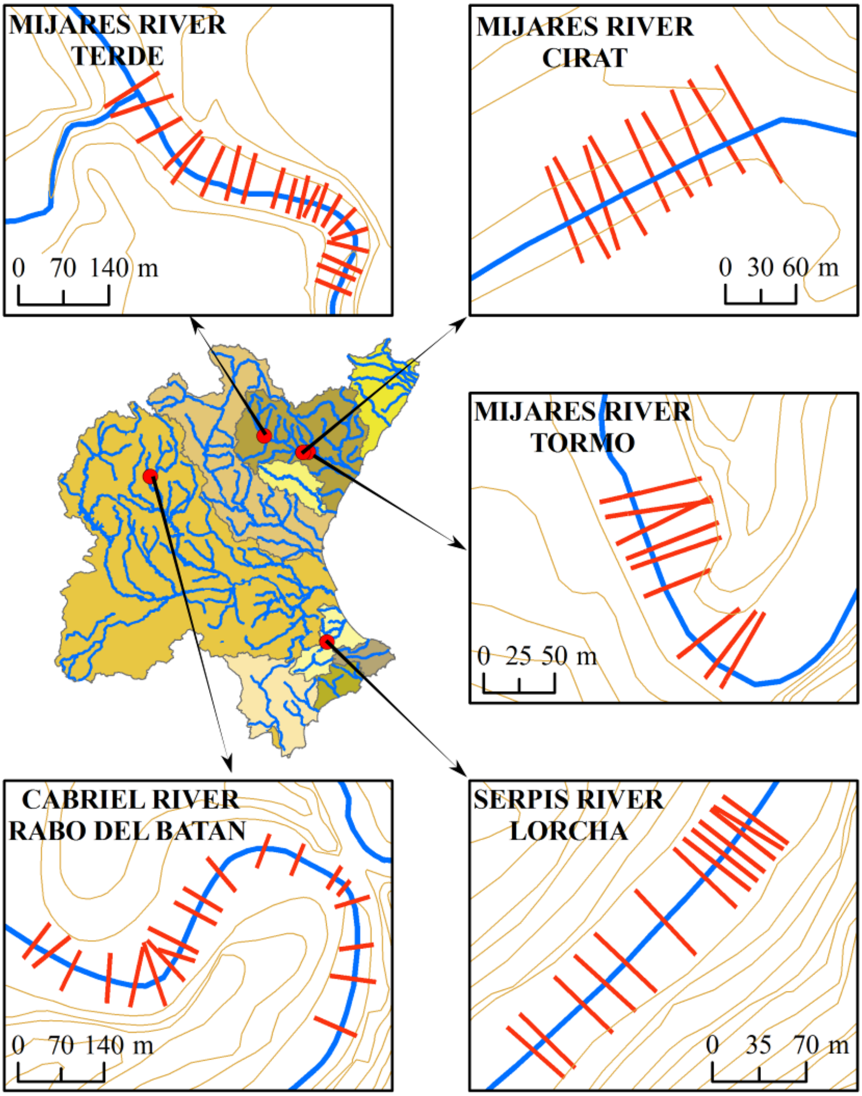


Figure 2.2. *Map of the Júcar River Basin District showing the study reaches and location of the transects. Sites located on the left are free-flowing and those sites located on the right are regulated.*

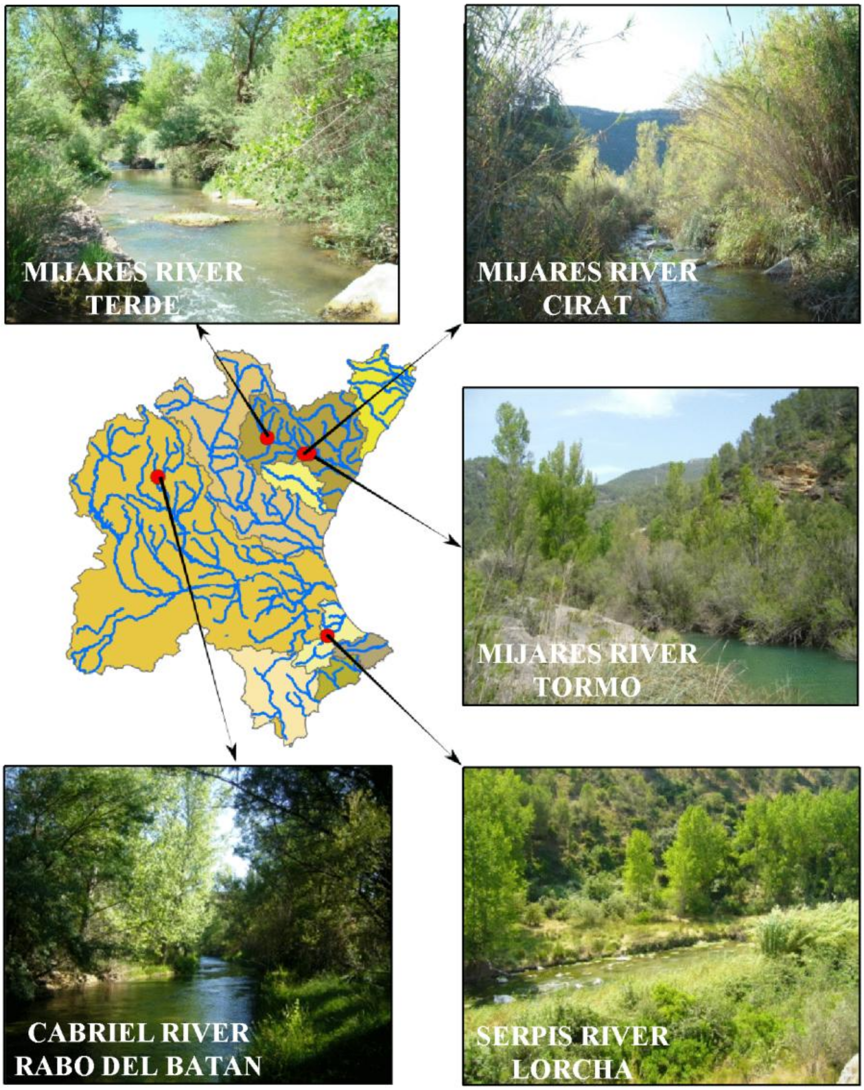


Figure 2.3. *Photographs showing typical views of the riparian zones along the studied rivers. Sites located on the left are free-flowing and those sites located on the right are regulated.*

2.4 METHODS

The field campaigns were carried out in different years, between 2006 and 2009, but during the same months (spring and summer), since species undergo changes in relative abundance through the year, particularly in response to seasons. Therefore, censusing at the same time of the year is a requirement when comparing sites or studying change over years (Bullock, 2006).

2.4.1 Geo-referenced sampling of vegetation by transects

First part of this study was the survey of the woody riparian species (shrubs and trees) along transects perpendicular to the stream flow and valley axis (cross-sectional transects; **Figure 2.2**), following the 'line intercept method' (firstly described by Canfield, 1941).

Transects encompassed the river channel and the complete floodplain, which is the zone built of sediments deposited by the river and vegetated by riparian species, such as willows, poplars, tamarisks, etc. Transects finished upslope, where stands dominated by terrestrial vegetation or agricultural uses were dominant. Therefore, their length was variable, depending on the river valley width and land uses.

The cross-sections were marked out with one steel rod (landmark) in every riverbank. Absolute coordinates (X, Y and Z) were assigned to the top of each steel rod using a GPS, model Leica® 1200 RTK (composed by two units: base station and rover). This GPS of high precision was used in first place because it was necessary to get good data of the rods, as they were the fixed reference to geo-reference all the vegetation points. For those rods located in densely vegetated areas where the GPS signal was weak, a total station FOIF® was used instead to geo-reference them.

Figure 2.4. *Assignation of absolute coordinates to the site Mijares-Terde with GPS. Base station (left) and rover in the Molino geodesic point (centre) and in the study reach (right).*

Not all the individuals have the same probability to be recorded according to their shape and size, e.g., bigger plants are more likely to touch the transect than those smaller. For this reason, we used line transects but sampling vegetation within a certain distance of the line. This technique increases the number of plants sampled per unit length in comparison with the typical line transects (Greenwood and Robinson, 2006). In our case, we recorded the vegetation units intercepting the transect line, as well as those vegetation units within two meters apart from the line, since they can be considered under the same conditions than those located just in the line.

As specified before, our sampling unit during the field survey was the *vegetation unit*. It consists of just one plant or a distinct group of plants (several stems) of the same species and age, located in a reduced place and under the same conditions (rather uniform soil characteristics, distance and elevation above water level). In this sense, we identified the vegetation units touching the transect and those close to it and we recorded two points per vegetation unit, one at the beginning and another at the end of the vertical projection of the crown of the plant (or group of plants) on the ground surface and projected on the transect line. For each vegetation unit sampled, the number of stems was recorded.

This type of transects could be considered as small *gradsects* (gradient-directed transects), which are laid out to sample intentionally the full range of floristic variation over a study area. It is usually positioned to lie along a steep environmental gradient, as shown in the next figure.

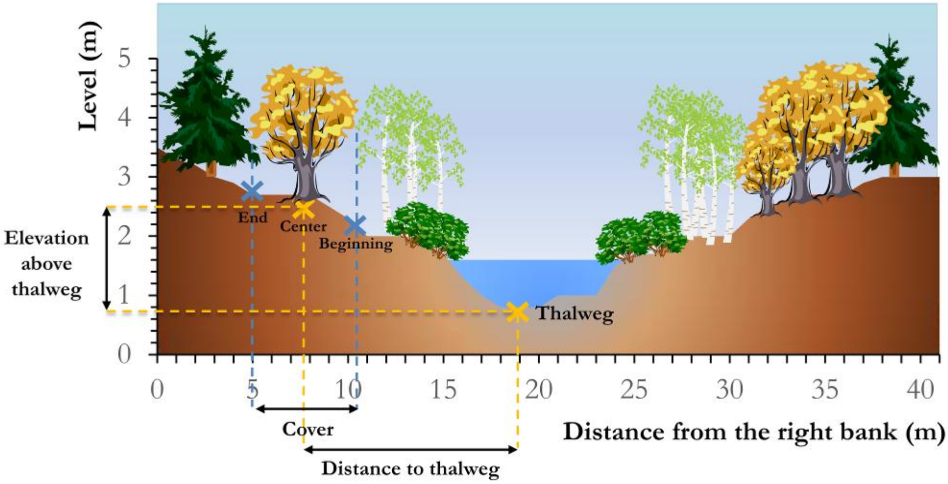


Figure 2.5. *Cross-sectional view of one theoretical transect. The position of the points recorded in the field are shown: beginning and end of the vertical projection (to estimate cover) and predicted ground surface level of the main stem (to estimate distance and elevation to/above thalweg).*

2.4.2 Comparison of observed and predicted ground surface for the trunk of the tree

The two topographic points measured per vegetation unit were used for several purposes (as can be seen later on), but it was necessary to define just one point per vegetation unit in order to compare among species. In this sense, we wanted to compare if the predicted centre of the vegetation unit was equivalent to the original one. To test this, the procedure explained below was carried out (**Figure 2.6**).

Three topographic measurements (first: beginning of the vertical projection; second: end of the vertical projection; and third: base of the trunk or main stem of the tree or shrub at the observed ground surface level) were taken for a subsample of plants in the Mijares-Terde study reach. This was done using an autolevel transit and a stadia rod. After taking the three measurements, we checked that the values of the differences between the upper and lower horizontal stadia marks with the centre crosshair of the reticle were equal, or at least smaller than 2 mm, which is the accuracy of this instrumentation.

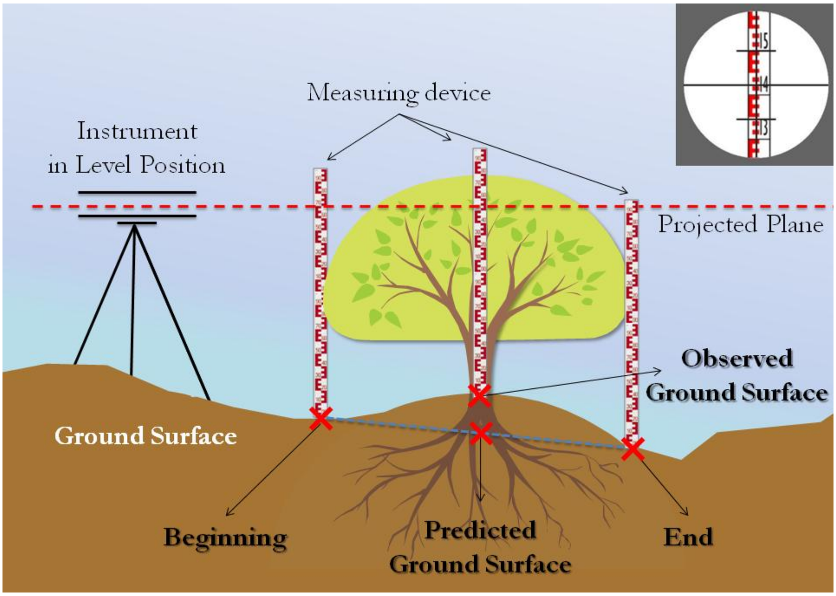


Figure 2.6. *Topographic points measured in a subsample of riparian plants of the Mijares-Terde study reach to test if significant differences exist between the observed and predicted ground surface level of the trunk of riparian trees and shrubs.*

The robust Yuen's t-test for paired (R function *yuend*) was used to assess if there were significant differences between the observed ground surface level of the trunk of the tree (measured in the field) and the predicted ground surface level for the same point (estimated from the beginning and end of the vertical projection of the plant). This test computes the confidence interval for $\mu_{t1} - \mu_{t2}$, the difference between the trimmed means corresponding to two dependent groups (García-Pérez, 2005; Wilcox, 2012). Using the trimmed mean the sensitivity of the arithmetic mean to extreme observations is reduced. It involves discarding a proportion of the outer observations on either side and averaging the remainder. The null hypothesis means that there are no significant differences (at a certain significance level) between both ground surface levels (the one observed in field and the one predicted or estimated). In this study, we estimated the 0.95 confidence interval for the difference between the 10 % trimmed means using the data stored in the two R vectors containing the values in **Table 2.2**. A bivariate boxplot or relplot (R function *relfun*) was created to identify outliers (García-Pérez, 2005; Wilcox, 2012).

2.4.3 Definition of variables and vegetation data analysis

2.4.3.1 Vegetation indicators

Transects are commonly used to survey changes in vegetation along an environmental gradient; additionally, a second use is to estimate overall density or cover value of species in an area (Bullock, 2006). Thus, different approaches were used to characterize the riparian vegetation community of each study reach, based on the data recorded by transects. The vegetation indicators were the following:

- **Richness.** Total number of species sampled in each study reach.

- **Abundance**. Number of individuals (stems) of each species within the transects. It is a measure of chance of finding an individual of a species in the sample area. The percentage of each species respect to the total number of plants sampled per site was estimated as well.

- **Cover**. It is a size-based measure of the area covered by the above-ground parts of plants of a species when viewed from directly above;

i.e., it is the proportion of ground (within the transects) occupied by the vertical projection onto it of the parts of all individuals of a species. Because the vegetation may be layered, the cover of all species often sums to > 100 %. In this study, we estimated the percentage cover of each species in relation to the total cover sampled.

- **Density.** It is the standard count of the number of organisms in a prescribed area. In this case, the density was assessed considering the meters of cover of each species per site (in relation to the total length of all the transects). Moreover, we estimated the number of stems of each species per site (in relation to the total length of all the transects). Therefore, we obtained two indicators of density: m of cover of a certain species per m of transect and, number of stems of a certain species per m of transect.

2.4.3.2 Calculation of the morphological variables

All the vegetation points recorded in the field with total station were imported into ArcGIS^{TM} version 9.3 (ESRI, Redlands, California, 2009). A straight line was drawn joining the steel rods of each transect. Then, the vegetation points were projected in this line in order to correct small deviations from the line during the surveys. From the topographic information of each transect, the thalweg was identified as the deepest point of the channel bed. Then, the coordinates of the centre of each vegetation unit were obtained (using the beginning and end points of each vegetation unit). Then, we calculated the location relative to the thalweg for all the species, i.e., relative linear distance from the vegetation unit to thalweg and relative elevation (vertical distance) from the vegetation unit above thalweg (**Figure 2.5**).

2.4.3.3 Intra and inter-sites comparisons

For each site, the location of the different riparian species recorded was compared based on the two key variables, i.e., distance and elevation (using boxplots) and the Huber estimator was calculated for each species. The Huber estimator belongs to a class of estimators called M estimators that represent a compromise between the mean and the median. It is obtained by minimising a term involving the sum of errors. Therefore, it could be defined as a robust estimate of location (i.e., population mean) that reduces the effects of the outliers in the data (García-Pérez, 2005).

In addition, dominance curves were developed for all the species in each site, in order to assess the abundance of each one (frequency) and the habitat suitability of different small patches (5 m wide and 0.5 m high) along the entire lateral gradient on the riparian zone. Then, the location of coincidence species among sites (i.e., species present in more than one site) was compared to test if they showed the same patterns in unregulated and regulated sites.

Robust and non-parametric statistics were applied for most of the calculations because the distribution of species in the riparian corridor did not follow a normal distribution. Furthermore, the presence of outliers in these distributions made necessary the use of robust statistics, which reduce the possible influence that those outliers could have in the analyses. In this sense, a robust analysis of variance was carried out (robust Welch one-way ANOVA; R function *t1way*) to contrast the null hypothesis of equality in the parameters of position of the *r* independent populations, because the usual hypotheses of normality and homoscedasticity (equal variances) could not be assumed. We wanted to contrast the null hypothesis (H_0) of equality of means for all the riparian woody species in relation to the two key variables (distance and elevation to/above thalweg), *versus* the alternative hypothesis (H_1) of not being all the means the same.

$$H_0 : \mu_{\alpha,SP} = \mu_{\alpha,PA} = \mu_{\alpha,PN} = \mu_{\alpha,FA} = \ldots = \mu_{\alpha,r}$$

$$H_1 : \mu_{\alpha,SP} \neq \mu_{\alpha,PA} \neq \mu_{\alpha,PN} \neq \mu_{\alpha,FA} \neq \ldots \neq \mu_{\alpha,r}$$

In all cases, these comparisons make use of sample α-trimmed means $\bar{x}_{\alpha,SP}, \bar{x}_{\alpha,PA}$, ..., $\bar{x}_{\alpha,r}$, obtained after sampling in the *r* populations to be compared, and using samples of size n_{SP}, n_{PA}, … n_r. The amount of trimming (hereafter, *tr*) and the significance level (hereafter, α) were the same in the *r* populations (10 % and 0.05 in most cases). The null hypothesis (H_0) was rejected for large values of the *FWe* statistic, which follows an F Snedecor distribution if H_0 is true.

When the null hypothesis was rejected, a test for multiple comparisons (R function *lincon*) was applied to define groups of species with the same behavior in relation to the variables analyzed. The significance level applied was α = 0.05 and the trimming percentage *tr* = 10 %.

2.4.4 Soil sampling and analysis

Soil samples were collected in each one of the study reaches (**Figure 2.7**). The surveyors walked along each site drawing a sketch of the different types of soils and writing a short description of them. After that, all the information recorded about each site was summarized and several points were selected to be sampled, covering the lateral and longitudinal gradient of the river, i.e., the points were localized in representative soil types and covering from the area near to the water's edge to the upland and from upstream to downstream. In addition, a sketch of the soil types present in each one of the cross-sections was done during the field survey.

Figure 2.7. *Soil sampling in the soil types 5 (a) and 8 (b) of the Mijares-Terde reach.*

As a general rule, the samples were extracted by digging pits between 30 and 60 cm soil depth. From **Figure 2.8** can be easily appreciated the differences among soil samples in terms of texture, moisture and organic matter content.

Figure 2.8. *Appearance of some of the soil samples taken in the Serpis-Lorcha study reach ready to be analysed in the laboratory.*

The samples (labelled with a code) were analysed in a specialized Soil Laboratory of the Universitat Politècnica de València. Three analyses were conducted in order to define the texture and organic content of each sample. A short description of each analysis is provided:

- Particle size analysis by sieves test (UNE 103.101-95). This granulometric analysis employs a set of sieves of different size of mesh to separate the particles with bigger size (from 125 to 0.08 mm).
- Particle size analysis by sedimentation test: Hydrometer method (UNE 103.102-95). This method was used to determine the particle size distribution of very fine materials, such as silt and clay (i.e., from 0.08 to 0.001 mm).
- Determination of the oxidisable organic matter content by Potassium permanganate method (UNE 103.204-93).

The aforementioned methods allowed defining the following parameters for each soil sample:

- Percentage of gravel (particle size > 2 mm)
- Percentage of sand (0.05 mm < particle size < 2 mm)
- Percentage of silt (0.002 mm < particle size < 0.05 mm)
- Percentage of clay (particle size < 0.002 mm)
- Percentage of organic matter content

Additionally, the moisture content was determined for each soil sample by a gravimetric method, where the sample was weighted before and after oven-drying. The amount of soil moisture (in percentage) was calculated dividing the water loss (wet mass minus dry mass) by the oven-dry weight (dry mass).

A soil type (and hence, its characteristics: texture, organic matter and moisture content) was assigned to each individual sample in each cross-section. Barplots with error bars were drawn to illustrate the differences in the soil characteristics for each species. Statistical program R and the package *hmisc* (Harrell, 2010) was used for it. The error bars represented the boundaries for the confidence interval in which the true mean values laid somewhere (with 95 % chance). This interval was computed by subtracting/adding the adjusted standard error of the mean for the lower/upper value. The standard error is defined as the ratio of standard deviation to the square root of the sample size. The standard error is then adjusted to the level of trust you want to have for your approximation (mostly 95 %) by multiplying it with the confidence coefficients for the normal distribution. For a confidence level of 95% this value is 1.96. These values were used to compute the upper and lower vectors for the *errbars* function in R. For the lower values, we just subtracted the standard error from the means and for the upper values, we added it to the mean, respectively. Therefore, we constructed confidence intervals for the standard error.

2.4.5 Multivariate analysis

A multivariate approach using Principal Components Analysis (hereafter, PCA) and Cluster Analysis was used to define groups of species that respond in similar ways to certain variables. With these two techniques, plants were organised into non-phylogenetic groupings of species with similar response to the river morphology and soil characteristics, which ultimately depend on the flow regime.

Before implementing those analyses, the normality of the variables was tested, and no normality was found in any of them. However, the PCA was performed because when the purpose is just exploratory (not the inference), the normality of the variables is not a strict requirement. The variables used were: DIST_THW, distance to thalweg; ELEV_THW, elevation above thalweg; GRAVEL, percentage of gravel; SAND, percentage of sand; SILT, percentage of silt; CLAY, percentage of clay; OM, organic matter content; SM, soil moisture content. They were shifted (to be zero centered) and scaled (to have unit variance) before the PCA analysis took place. It was carried out using the function *prcomp* from the R package *stats* (R Development Core Team, 2010). Due to the small number of variables, all of them were retained in the graph, but only those with loadings higher than |0.7| were considered for interpretation.

The average scores for each species on each principal component was calculated. The values belonging to the first two components were overlaid onto the PCA plot, which represented the average value of each species. For better interpretation of the association between species and certain physical variables, such species' values were scaled. Then, a hierarchical cluster analysis was conducted, using for each species the average values of the scores on the first three principal components extracted from the PCA. This was useful for a better definition of the association among species.

The hierarchical clustering and resultant diagrams were generated with the function *hclust* from the package *stats* of R (R Development Core Team, 2010).

Firstly, a proximity matrix using Euclidean distance was generated from the PCA scores information. Then, the function *hclust* performed a hierarchical cluster analysis using a set of dissimilarities for the *n* species being clustered. Initially, each species is assigned to its own cluster and then the algorithm proceeds iteratively, at each stage joining the two most similar clusters, continuing until there is just a single cluster.

Average linkage clustering was selected as agglomeration method. It is the method recommended in community ecology because it seems to be more neutral in grouping and a compromise between single (nearest neighbour) and the complete (further neighbour) linkages (Oksanen *et al.*, 2011). In average linkage clustering, the distance between two clusters is the average distance between pairs of observations, i.e. the distance between two items *x* and *y* is the mean of all pair wise distances between items contained in *x* and *y*, therefore, this method merges in each iteration the pair of clusters with the highest cohesion (shortest average distance between members of both clusters). The resultant dendrogram or tree was cut at some fusion level in order to have a certain final number of clusters.

Additionally, the clustering results were displayed in ordination diagrams. The function *ordicluster* (within package *vegan* and compatible with *hclust*) overlays a cluster dendrogram onto ordination (based on the proximity matrix). It connects points (i.e., species) and cluster fusion points to each other with line segments similarly as in the original cluster dendrogram. According to Oksanen *et al.* (2011), overlaying classification in ordination can be used as a cross-check: if the clusters look distinct in the ordination diagram, (both) analyses probably were adequate.

The variability of the sites was evaluated using the classification strength developed by Van Sickle (1997) with the tool *EnvClass* (Snelder *et al.*, 2009) in the statistical package R (R Development Core Team, 2010). The results are shown in three dendrograms of dissimilarity according to the sites' status (natural *vs.* regulated), rivers and sites. The association within each group is compared with the mean dissimilarity between groups. The vertical line (trunk) of the dendrogram indicates the mean of all between-group dissimilarities ($\overline{B}$). The length of the horizontal lines (branches of the dendrogram) represents the between-group dissimilarity minus the within-group dissimilarity ($\overline{Wi}$), i.e. $\overline{B}-\overline{Wi}$. The larger the value of $\overline{B}-\overline{Wi}$ for the length of a branch to the left side, the more homogeneous the group is in relation to the whole dataset. The classification strength was evaluated with the indicator CS ($CS=\overline{B}-\overline{W}$). According to Van Sickle and Hughes (2000), CS values can range from 0, implying equal dissimilarity within and between classes (i.e., no class structure: $\overline{W}=\overline{B}$), to 1, implying no dissimilarity within classes (i.e., $\overline{W}=0$) and maximum dissimilarity between classes (i.e., $\overline{B}=1$). The statistical significance of this test was checked based on the null hypothesis of 'no class structure' through a random test using the bootstrap technique (number of bootstrap samples = 100; permutations = 100) (Goslee and Urban, 2007).

After analysing the variability of the different status, rivers and sites, a metric multidimensional scaling (MDS) was carried out to illustrate the groupings among sites. This method locates objects in a reduced multidimensional space according to the range of similarity between pairs of objects in a proximity matrix (Digby and Kempton, 1987). Hence, the closest points will correspond to the most similar objects. For a better interpretation of the data, only the mean positions of each object were shown in the two-dimensional plot.

2.5 RESULTS I

2.5.1 Comparison of observed and predicted ground surface level for the trunk of woody riparian shrubs and trees

The relplot function reported a correlation of 0.96 between both variables and showed just one point outside the larger ellipse (**Figure 2.9**); therefore a 10 % amount of trimming was established as appropriate.

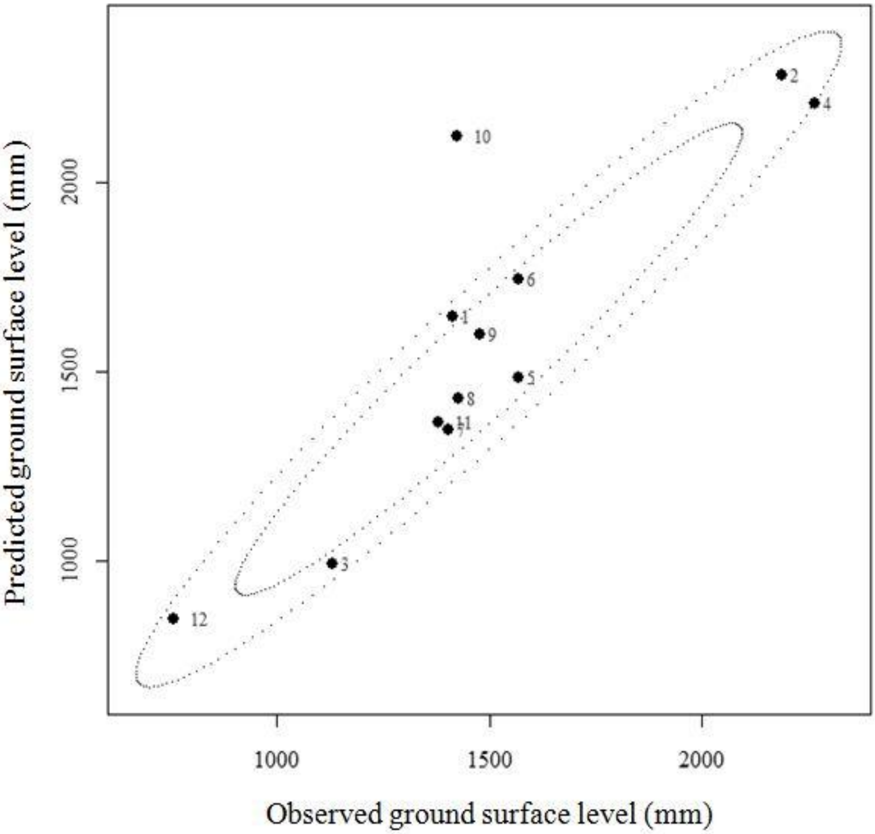


Figure 2.9. *Relplot for bivariate data representing the observed and predicted ground surface level of riparian trees and shrubs at the Mijares-Terde study reach. The smaller ellipse contains half of the data. Points outside the larger ellipse are considered to be outliers.*

Applying it to the data in **Table 2.2**, the R function *yuend* gave as result Ty = -1.17, the *p-value* (hereafter, *p*) was 0.27, and the 0.95 confidence interval for µt1 – µt2 was (-274.85, 87.65). Therefore, we did not reject the null hypothesis of equality of levels. In other words, there were no significant differences in the level of both points. Therefore, we could assume that the predicted estimation of the ground surface level was a good approximation of the 'real' base of the trees and shrubs at ground surface level in the field.

Table 2.2. *Observed and predicted ground surface level (mm) of the base of the trunk for a subsample of riparian plants in the Mijares-Terde study reach.*

Plant number	Observed ground surface level (mm)	Predicted ground surface level (mm)
1	1414	1643.5
2	2187	2282.5
3	1130	989.5
4	2266	2206
5	1570	1484.5
6	1570	1743.5
7	1404	1346
8	1428	1426.5
9	1477	1595.5
10	1423	2119.5
11	1379	1363.5
12	756	844.5

2.5.2 Vegetation description and comparison intra-sites

In this section, a detailed description of the riparian vegetation community of each study reach is provided using indicators (species richness, abundance, cover and density) and grouping the different species in relation to their positional patterns (distance and elevation to/above thalweg) and soils features.

Table 2.3. *Plant species surveyed by study reach along the Cabriel, Mijares and Serpis rivers (Júcar River Basin District, East Spain). In each cell appears the number of specimens (stems) surveyed for each species and reach. The scientific and common names of each species are indicated and the code assigned to each species during the survey and later analyses.*

Scientific name	**Common name**	**Code**	**Family**	**Cabriel- R.Batán**	**Mijares-Terde**	**Mijares- Cirat**	**Mijares -Tormo**	**Serpis - Lorcha**
Salix alba L.	White willow	SL	Salicaceae	34	28	-	-	-
Salix atrocinerea Brot.	Large gray willow	SA	Salicaceae	-	26	5	3	41
Salix eleagnos Scop.	Rosemary willow	SE	Salicaceae	75	46	20	19	-
Salix purpurea L.	Purple willow	SP	Salicaceae	76	178	5	-	-
Salix triandra L.	Almond willow	ST	Salicaceae	6	-	-	-	-
Populus alba L.	White poplar	PA	Salicaceae	293	-	-	-	33
Populus nigra L.	Black poplar	PN	Salicaceae	116	110	36	18	44
Fraxinus angustifolia Vahl	Narrow-leaved ash	FA	Oleaceae	61	-	-	-	-
Nerium oleander L.	Oleander	NO	Apocynaceae	-	-	2	36	61
Tamarix spp.	Tamarisk	TA	Tamaricaceae	-	-	16	17	-
Coriraria myrtifolia L.	Redoul	CM	Coriariaceae	-	-	23	22	-
Crataegus monogyna Jacq.	Common hawthorn	CR	Rosaceae	16	-	-	-	23
Viburnum tinus L.	Laurustinus	VT	Caprifoliaceae	-	-	-	18	4
Cornus sanguinea L.	Common dogwood	CS	Cornaceae	8	-	-	-	-
Pinus spp.	Pine	PC	Pinaceae	154	-	-	-	-
Juniperus spp.	Juniper	JU	Cupressaceae	-	132	-	-	-
Quercus coccifera L.	Kermes oak	QC	Fagaceae	-	40	-	-	-
Quercus ilex L.	Holm oak	QI	Fagaceae	-	7	-	-	-
	Total			**839**	**567**	**107**	**133**	**206**

2.5.2.1 Cabriel – Rabo del Batán

2.5.2.1.1 Vegetation description

The number of transects surveyed at Cabriel-Rabo del Batán reach was 20. Their mean length was 69 m and their range was from 30 m to 106 m. The plant richness was 10 (five tree species and five shrub species) (**Table 2.3**) and 839 was the total number of plants recorded. The total length of transects surveyed was 1380 m and the length of plant cover 1934 m, which depicted a total cover of 140 %, meaning that several strata or vegetation layers were overlapped in some parts of the site. More specifically, 32 % of the total cover was formed by shrub species and 108 % by tree species. As can be seen in **Figure 2.10**, the most abundant species were *Populus alba* (PA), *Pinus* spp. (PC) and *Populus nigra* (PN), with 35 %, 19 % and 14 % of the total number of stems, respectively, indicating that this site has a mature riparian forest, as both the percentage of stems and cover were dominated by these three tree species. The percentages of stems and cover were similar for all the species, except for *Salix alba* (SL) and PA. In the case of SL, 4 % was the percentage of stems and 6 % the percentage of cover. This revealed that this species presented few and old individuals. In contrast, PA exhibited larger percentage of stems than cover (35 respect to 30 %), which meant that despite being the most abundant tree species, many of its individuals were small.

In relation to the density, PA showed the highest values. For each m of transect sampled, 0.4 m were covered by this species and additionally, this corresponded to 0.2 stems, i.e., in every ten m of transect two stem of PA were present with a total cover of four m. Complementary, both PC and PN were characterized by 0.1 stems, and 0.3 and 0.2 m of cover per m of transect, respectively. Using the same previous example, per every ten m of transect one stem of PC and one of PN were present with a cover of two and three m respectively. *Salix purpurea* (SP), *Salix eleagnos* (SE), *Fraxinus angustifolia* (FA) and SL appeared to have similar density in the study reach (0.1 m of cover per m of transect). Nevertheless, FA and SL showed lower values of stems/m than SP and SE, probably because the first two species are trees and the second two species are shrubs.

Finally, *Salix triandra* (ST), *Cornus sanguinea* (CS) and *Crataegus monogyna* (CR) were the species with smaller abundance, cover and density in the study reach. ST and CR had similar cover values, but ST had smaller number of stems.

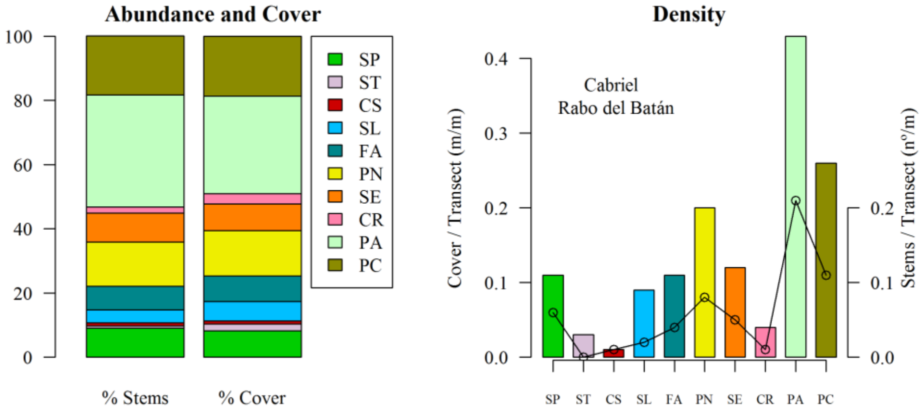


Figure 2.10. *Descriptors of the woody riparian species sampled by transects at the Cabriel-Rabo del Batán study reach. Left plot shows abundance (percentage of stems of each species respect to the total number of plants sampled) and cover (percentage of cover of each species respect to the total cover value in the site). Right plot shows density (bars indicating meter of cover of each species per meter of transect, left axis; and points indicating number of stems of each species per meter of transect, secondary axis). Codes are noted in* ***Table 2.3****. Species appear in ascendant order according to the ranking defined by the Huber estimator in the elevation above thalweg.*

2.5.2.1.2 Distance and elevation above thalweg

Differences in the positional pattern of the riparian species were detected in the Cabriel River. In relation to distance to thalweg (**Figure 2.11 – left**), the robust test of Welch gave a value of $FWe = 51.14$ ($p = 0$), therefore we rejected the null hypothesis of equal 0.1-trimmed means. The test for multiple comparisons showed four homogeneous groups of species in relation to their distance to thalweg, considering $tr = 10$ % and $\alpha = 0.05$. These were: [CS, ST, SL, SP], [ST, SL, FA, SP], [SP, PN, CR] and [PA, CR, SE, PC]. However, considering only the species with larger sample size and $tr = 20$ % and $\alpha = 0.10$, the groups obtained were the following: [SL, FA, SP, PN], [SL, FA, SP], [SL, SP, PN] and [PA, SE, PC]. The species FA and PN did not appear together.

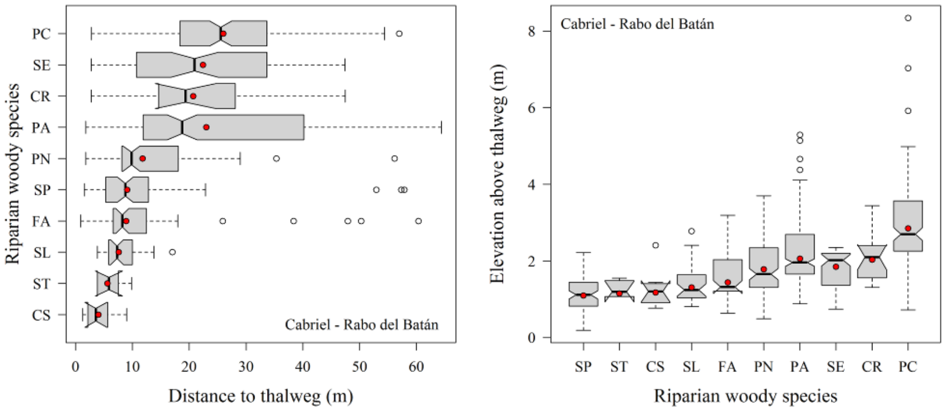


Figure 2.11. *Boxplots of the distribution (left plot - distance to thalweg; right plot - elevation above thalweg) of the woody riparian species sampled at the Cabriel-Rabo del Batán study reach. Species are in ascendant order according to their median values. Red dots represent the Huber estimator.*

In relation to elevation above thalweg in the Cabriel River, the robust test of Welch gave a value of $FW_e = 38.35$ ($p = 0$), therefore we rejected the null hypothesis of equal 0.1-trimmed means. Considering only the species with larger sample size, $tr = 20$ % and $\alpha = 0.10$, the test for multiple comparisons showed four homogeneous groups of species: [SP, SL], [SL, FA, PN], [PN, PA, SE] and [PC].

2.5.2.1.3 Dominance curves

The dominance curves revealed the locations where each species was more abundant, and therefore, we could guess the highest habitat suitability in those places. In relation to distance to thalweg (**Figure 2.12**), CS had its highest abundance values in the range 0-5 m from thalweg; ST, SP, SL, PN and FA in the range 5-10 m; SE and PA in the range 10-15 m and PC in the range 20-25 m. CR appeared under tree cover in a wide distance from thalweg, but it was specially abundant in the range 10-30 m. However, CS had a more reduce abundance for those places close to the water's edge, located at less than 10 m from thalweg.

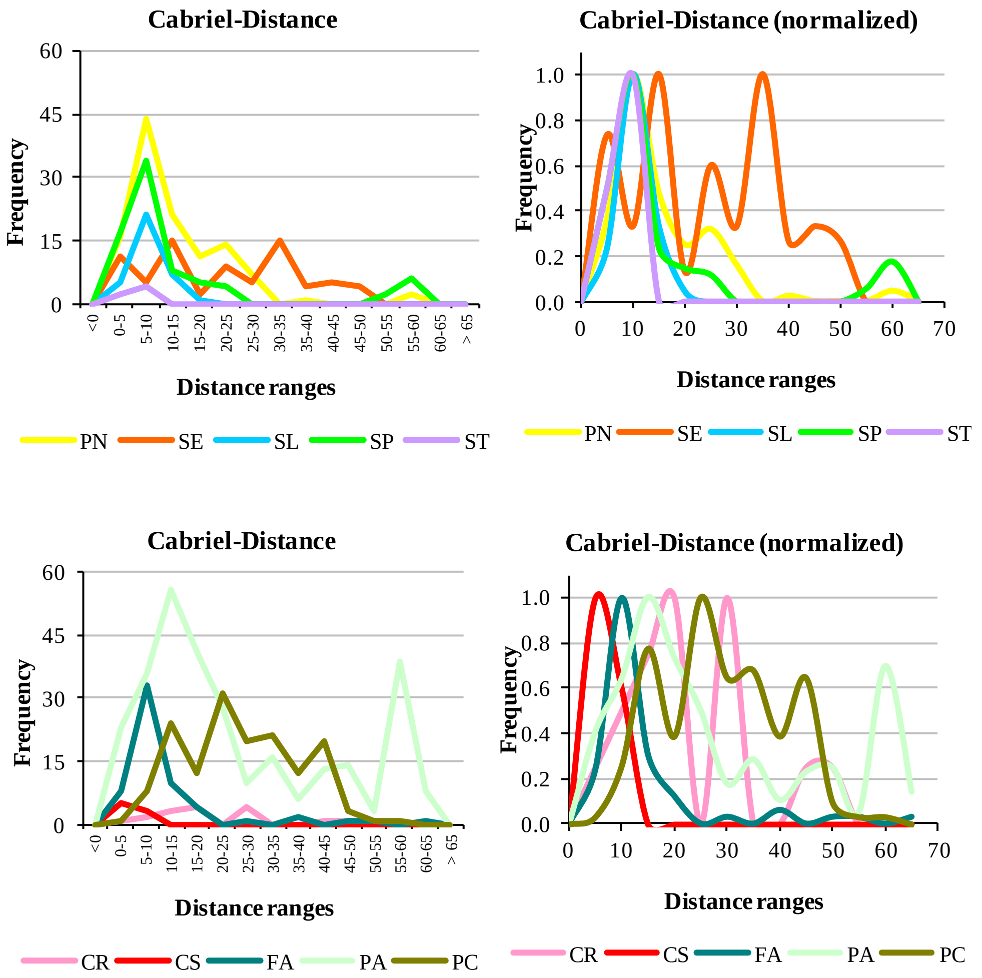


Figure 2.12. Dominance curves of the riparian species respect to the distance to thalweg at the Cabriel-Rabo del Batán study reach. To improve the visualization, species are shown in two separated graphs.

FA showed a disperse distribution along the entire riparian zone, but it was particularly abundant in the range 5-10 m from thalweg. Along with FA, four species more (PA, PC, SE and PN) occupied the entire distance gradient. PA was abundant from 0 to 25 m and had a second peak/maximum in the range

55-60 m due to the presence of a secondary channel only flooded in rainy periods. PN and SP showed a few exemplars at this location as well. SE showed a second peak at the range 30-35 m. In this case, that is an area between both channels and has a coarse substrate.

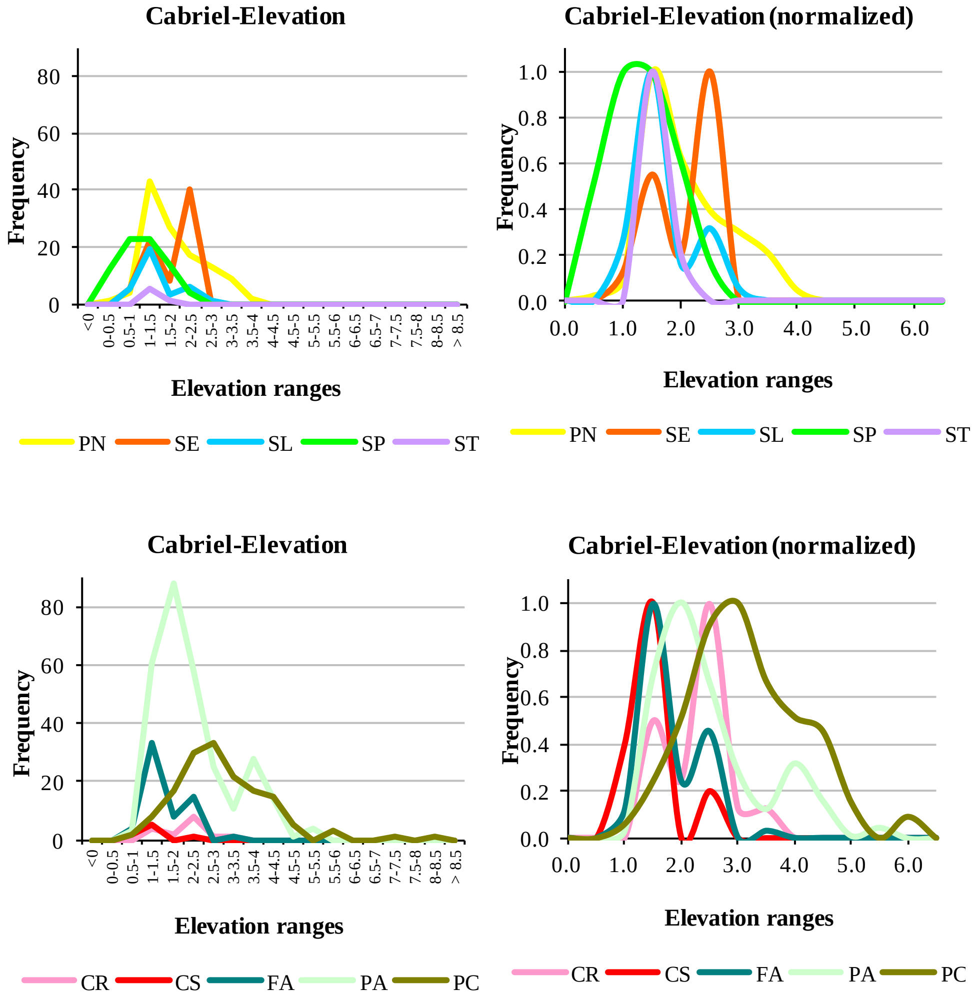


Figure 2.13. *Dominance curves of the riparian species respect to the elevation above thalweg at the Cabriel-Rabo del Batán study reach. To improve the visualization, species are shown in two separated graphs.*

In elevation above thalweg (**Figure 2.13**), the vast majority of the individuals were located from 0 to 3 m. SP and PN, which are two of the most pioneer riparian species, started at the lower locations (0-0.5 m above thalweg). The highest abundance of SP took place in the range 0.5-1.5 m, dominating in the range 0.5-1 m. ST, SL, PN, FA and CS had their largest abundance values in the range 1-1.5 m, being at that band PA, followed by PN and FA the dominant species in number. PA showed the widest distribution along the elevation gradient, but it was dominant in the range 1.5-2 m, accompanied by PN and PC. In the next range (2-2.5 m), SE and CR were the species showing their highest values for their own species, but the dominant species were PA, SE and PC. Finally, PC dominated and presented its highest abundance values in the range 2.5-3 m, along with PA and PC.

2.5.2.1.4 Soil characteristics

Twelve soil samples were analysed in this study reach. They differed in their grain size distribution (**Figure 2.14**). Soils 2, 5, 7, 10 and 12 were classified as gravel soils (gravel content > 68 %); soil 1 as gravel-sandy soil (50 % sand and 30 % gravel); soils 4 and 9 as sandy soils, as their sand content was > 80 %; and soils 3, 6, 8 and 11 as silty-sandy soils due to they were formed by a range of 20-50 % sand and 30-60 % silt. No clayey soils were found in the reach.

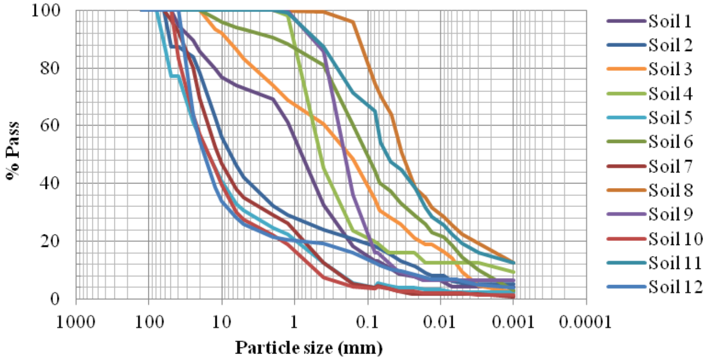


Figure 2.14. *Grain size distribution of the soil samples of the Cabriel-Rabo del Batán study reach.*

In all of the soils, the organic matter was less than 5 % and the moisture content was in the range 3-60 %. A correspondence was observed between soils with larger percentage of organic matter content and larger moisture content (**Figure 2.15**).

In relation to the soil properties (**Figure 2.16** and **Figure 2.17**), we could distinguish groups of species with high or low association with a specific soil parameter, however there was a clear overlap among species (except for PC, which appeared in most of the cases clearly differentiated from the rest of species). The species with small sample size (ST, CS and CR) were not considered in the comparisons because their results could be misleading. However, they were kept in the graphs and a small qualitative description of their soil preferences appears at the end of this section.

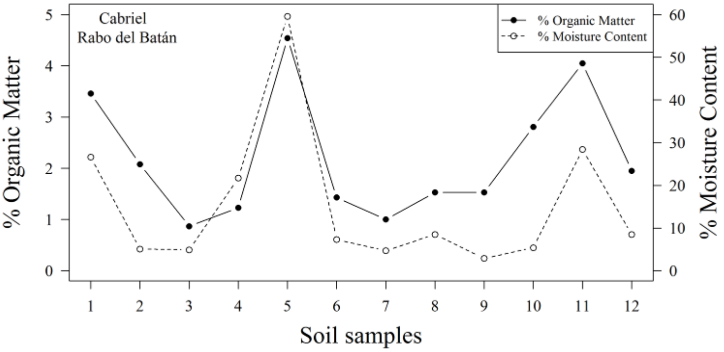


Figure 2.15. *Percentages of organic matter and moisture content in the twelve soil samples analyzed in the Cabriel-Rabo del Batán study reach.*

In the case of the gravel content, PC showed higher percentages (hence, PC was located in places with larger grain size, in the riparian zone as well as in the slopes) than the rest of the species, showing significant differences with SP, SL and PN, which had smaller gravel contents. The rest of the species showed intermediate values as average but in general, all the species showed a high variability. SL and SP had a standard deviation of 26 and 29 % respectively, whereas the rest of species had values in the range 33-37 %. On the contrary, PC presented the smallest percentage of sand (25 %) and showed significance differences with the rest of species, showing values in the range 32-39 %. PN got the smallest standard deviation (17 %) and SE the highest (24 %).

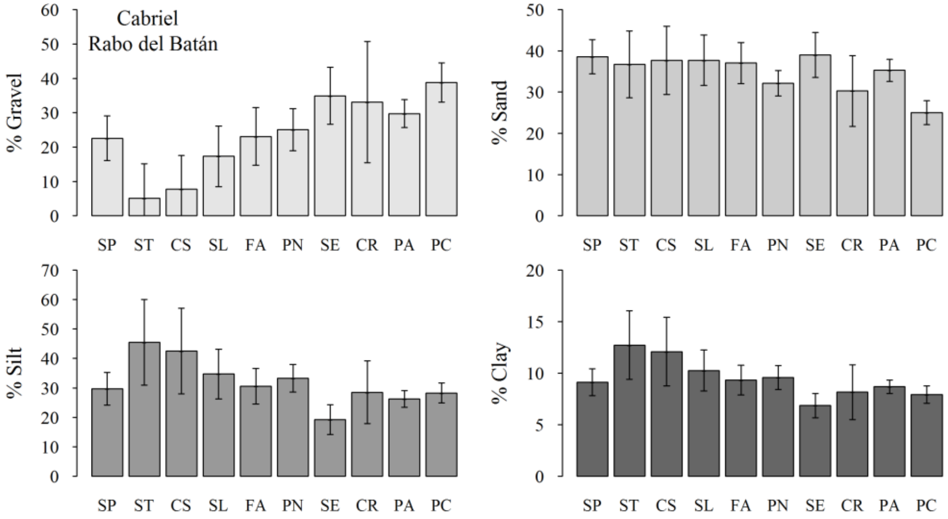


Figure 2.16. *Barplots with error bars for the percentage of gravel, sand, silt and clay for each species at the Cabriel-Rabo del Batán study reach. The height of the bars represents the mean values and the whiskers represent the confidence interval for the standard error. Species appear in ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.*

In relation to the silt percentage, significant differences were found only between PN and SE. In fact, SE got the smallest values (19 % of silt). Looking at the entire set of species, two groups could be defined, a first group with lower silt content formed by SP-SE-PA-PC (range of mean values: 19-30 %; range of median values: 10-14 %) and a second group with higher silt content by SL-FA-PN (range of mean values: 30-35 %; median value 51 %). The standard deviation was in the range 22-26 %.

In general, the percentage of clay was small in all the soil samples (16 % was the maximum value obtained; soil 8). Visually, two groups could be distinguished: SP-SE-PA-PC with lower content of clay (range of mean values: 7-9 %, and of median values: 4-6 %), and SL-FA-PN with higher content of clay (range of mean values: 9-10 %; median: 14 %), however significant differences were found only between PN and SE. The standard deviation was 5-6 %.

The percentage of organic matter content was high in the species SP-FA-SE (3-3.3 %), intermediate in SL-PN-PA (2.5-2.7 %) and low in PC (1.9 %). Significant differences were found between PC and the rest of species and also between FA and PN, SE and PN, and SE and PA, it is for this reason that they were classified into different groups. The standard deviation was in the range 0.8-1.4 %.

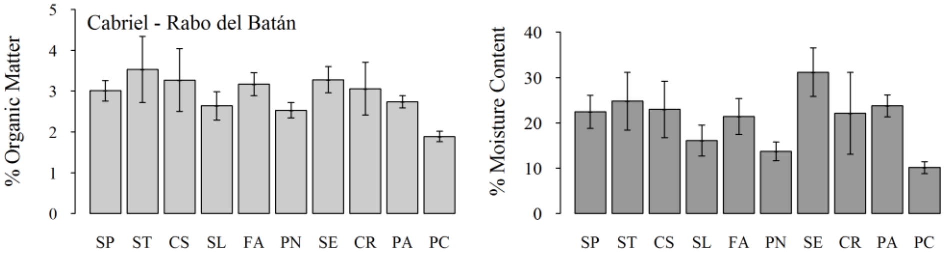


Figure 2.17. *Barplots with error bars for the percentage of organic matter and moisture content for each species at the Cabriel-Rabo del Batán study reach. The height of the bar represents the mean value and the whiskers represent the confidence interval for the standard error. Species appear in ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.*

The percentage of moisture content showed similar groups as the texture. Using the same test parameters (*tr* = 10 %; α = 0.05), three groups could be defined: SP-FA-SE-PA with higher moisture content (range: 21-31 %) respect to PN-SL (14 and 16 %, respectively). PC obtained the lower moisture value (10 %). SE had the largest standard deviation (24 %).

Finally, a few lines for the species with lower sample size. CS and ST showed similar patterns. They were located close to the water's edge, therefore in soils with high moisture content and organic matter. Basically, those soils were constituted by fine texture, such as sand, silt and clay, whereas the gravel content was very low. CR showed a completely different behavior, it was more similar to that showed by species far apart from the water's edge such as PN, PA and PC, i.e., higher grain size (basically gravel and sand).

2.5.2.1.5 Multivariate interpretation

A Principal Component Analysis (hereafter, PCA) and a Cluster Analysis were performed in order to analyze the joint variation of all physical variables (morphology and soil characteristics) and obtain groups of species with a similar response in a multivariate way. This interaction between species and physical variables is illustrated in **Figure 2.18**, where the first two axes of the PCA explained 66.1 % of the total variance. The variables positively related to axis 1 were DIST_THW (0.7) and GRAVEL (0.9), while SILT (-0.8) and CLAY (-0.8) were negatively related. The second axis was positively related to OM (0.7) and negatively to ELEV_THW (-0.8).

With the goal of helping to define groups of species with similar response, a classification analysis was performed on the coordinates of the first three PCA components, which explained 85.8 % of the total data variability (**Figure 2.19**).

In this sense, ST and CS were located in areas of low distance and elevation above thalweg (i.e. bank zone) with high content of sand and organic matter. In the center of the plot appears a group of riparian species that could be divided into two groups within the floodplain. A first band would be composed of SP and FA, close to the water's edge and with high organic content and soil moisture. They would be followed by a second band formed by PA and CR, farther from thalweg and with coarser substrate. Finally, as a differentiated group would appear PC, in areas of high elevation and coarse substrate (mainly gravel) and with low soil moisture and organic matter content, revealing a transitional change from riparian to terrestrial conditions.

SL and PN could be defined as the species marking the transition between the aforementioned groups within the floodplain. SE would be located near PA-CR but in coarser areas (with low content of silt and clay) and high soil moisture and organic matter content.

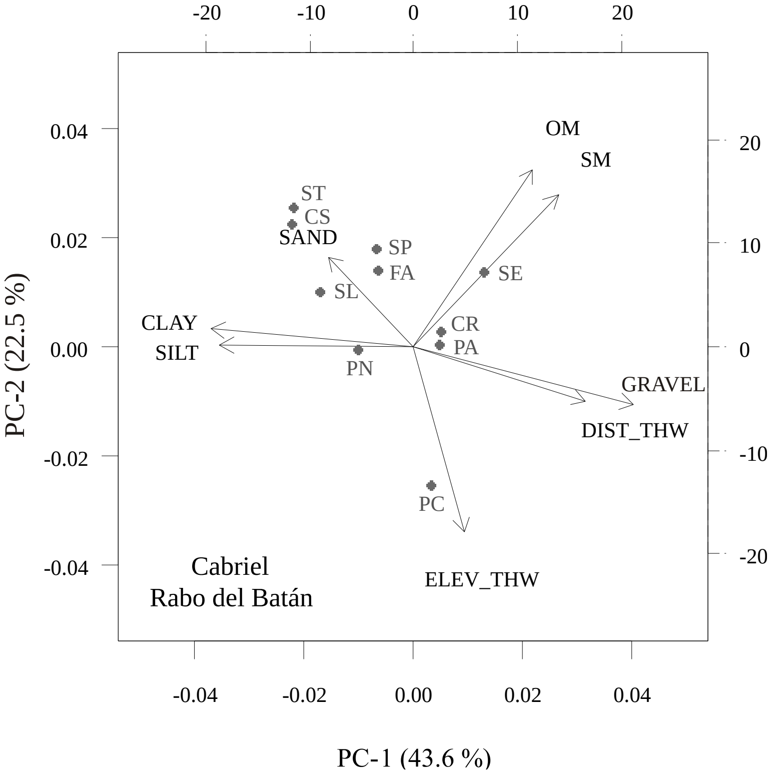


Figure 2.18. *PCA (principal components analysis) diagram for the Cabriel-Rabo del Batán study reach. Woody riparian species (dots in grey colour) are abbreviated as: ST, Salix triandra L.; CS, Cornus sanguinea L.; SL, Salix alba L.; SP, Salix purpurea L.; FA, Fraxinus angustifolia Vahl; PN, Populus nigra L.; PA, Populus alba L.; CR, Crataegus monogyna Jacq.; SE, Salix eleagnos Scop.; PC, Pinus spp.*

In short, considering the information given by the three analyses (PCA, cluster and ordicluster), seven riparian groups could be defined at the CRA according to its river morphology and soil characteristics, as follow: [CS-ST] [SP-FA], [SL], [PN], [PA-CR], [SE], [PC]. Grouping them into a smaller number of groups they would be defined as: [CS-ST] [SP-FA-SL-PN], [PA-CR-SE], [PC].

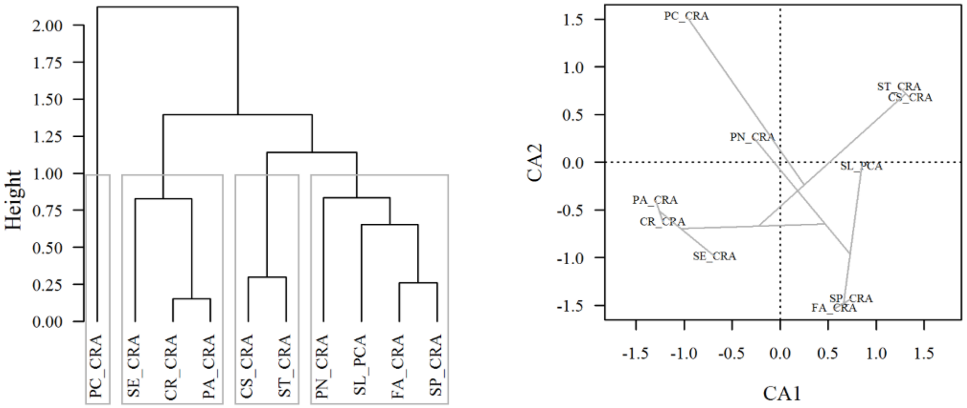


Figure 2.19. *Left plot, hierarchical cluster dendrogram (average clustering with Euclidean distance) based on the first three PCA scores for the woody riparian species recoded at the Cabriel-Rabo del Batán study reach. The vertical axis shows the level of fusion and is based on the dissimilarities between species. Right plot, clustering results overlaid onto an ordination diagram based on the proximity matrix. Cluster centroids are connected to each other with line segments similarly as in the original cluster dendrogram.*

2.5.2.2 Mijares – Terde

2.5.2.2.1 Vegetation description

The number of transects surveyed at Mijares-Terde was 20. Their mean length was 70 m and their range was from 54 m (the shortest transect) to 100 m (the longest one). The plant richness was eight (four tree species and four shrub species; five of them properly riparian) (**Table 2.3**) and 567 was the total number of plants recorded. The total length of transects surveyed was 1406 m and the length of plant cover 1101 m, which depicted a total cover of 78 % for the entire site. Some areas were uncovered (bare soil areas) and other portions of the site were cover by non-woody riparian species, such as upland grassland and common reed (*Phragmites australis*).

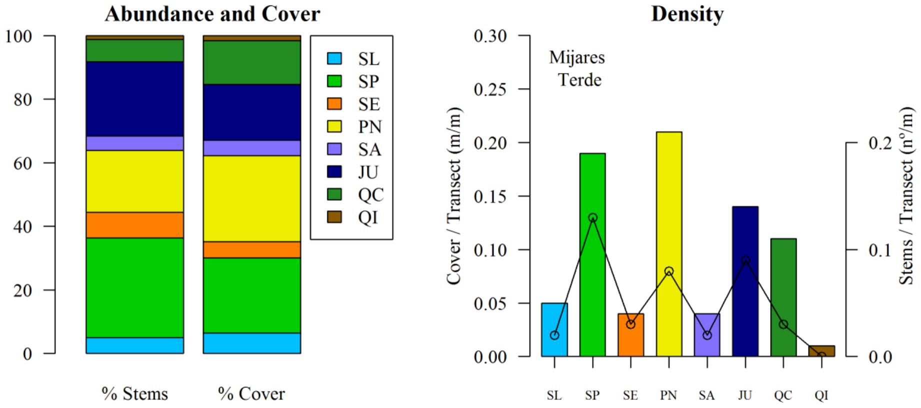


Figure 2.20. *Descriptors of the woody riparian species sampled by transects at the Mijares-Terde study reach. Left plot shows abundance (percentage of stems of each species respect to the total number of plants sampled) and cover (percentage of cover of each species respect to the total cover value in the site). Right plot shows density (bars indicating meter of cover of each species per meter of transect, left axis; and points indicating number of stems of each species per meter of transect, secondary axis). Codes are noted in* ***Table 2.3****. Species appear in ascendant order according to the ranking defined by the Huber estimator in the elevation above thalweg.*

As can be seen in **Figure 2.20**, the most abundant species were *Salix purpurea* (SP), *Juniperus* spp. (JU) and *Populus nigra* (PN), with 31, 23 and 19 % of the total number of stems, respectively. The rest of species were much less abundant, such as *Salix eleagnos* (SE), *Quercus coccifera* (QC), *Salix alba* (SL) and *Salix atrocinerea* (SA), (with 8, 7, 5 and 5 % of stems).

In relation to cover, PN showed the highest values (27 % of the total cover), followed by SP (24 % of cover). PN had higher values for cover than for abundance, what suggested old poplars. JU presented higher values for abundance than for cover (23 % respect to 18 %), while QC presented the opposite pattern (7 % respect to 14 %), suggesting that QC formed extensive patches with high cover and JU was represented by disperse individuals of low cover. SA, SE and SL showed similar values for abundance and cover.

In relation to the density, PN showed the highest values (for each m of transect sampled, 0.21 m were covered by this species and additionally, this corresponded to 0.08 stems). However, SP showed the highest density of stems per m of transect (specifically, 0.13 stems/transect). JU and QC presented intermediate values of cover (around 0.12 m of cover per m of transect). SL, SE and SA showed lower values than 0.05, and QI exhibited the lowest values for both, density of stems and cover.

2.5.2.2.2 Distance and elevation above thalweg

As can be seen in **Figure 2.21**, the riparian species appeared overlapped in the same distance and elevation ranges, and the proper terrestrial species (i.e., JU, QC and QI) were observed in farther positions, although they appeared as well in the upper range where the riparian species were located, revealing an ecotone or gradual transition between both groups of species. QI was shown in the boxplots to identify its patterns (but not considered in the test for multiple comparisons, due to its small sample size), which were similar to those showed by QC and JU in terms of elevation but it appeared farther in distance to thalweg.

The robust test of Welch gave a value of *FWe* = 57.68 (*p* = 0), therefore we rejected the null hypothesis of equal 0.1-trimmed means of distance to thalweg (**Figure 2.21 – left**). The test for multiple comparisons showed differences between the riparian and terrestrial species. Among the riparian species, significant differences were detected between PN and SA with *tr* = 10 % and α = 0.05. Therefore, the groups of homogeneous species found were: [JU, QC], [PN, SE, SL, SP] and [SA, SE, SL, SP]. The consideration of a higher trimming or a higher significance level eliminated the differences between PN and SA, revealing just two groups: terrestrial and riparian species. This fact can be visually appreciated looking at the Huber estimator. JU and QC had the highest values (26.6 and 26.9 m, respectively), whereas the riparian species exhibited values hovering around 7 and 9 m.

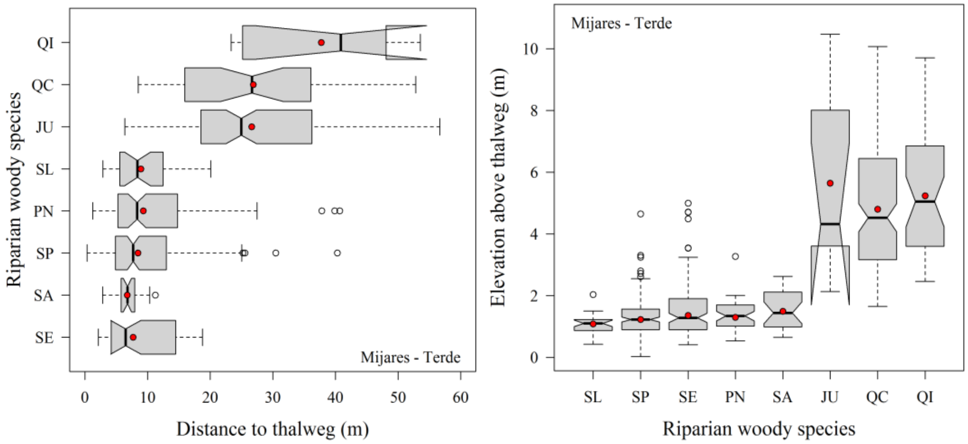


Figure 2.21. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the woody riparian species sampled at the Mijares-Terde study reach. Species are in ascendant order according to their median values. Red dots represent the Huber estimator.*

In relation to the elevation above thalweg (**Figure 2.21 – right**), the robust test of Welch gave a value of *FWe* = 70.89 (*p* = 0), therefore we rejected the null hypothesis of equal 0.1-trimmed means. The test for multiple comparisons (*tr* = 10 % and α = 0.05) showed significant differences in the elevations of the proper terrestrial species respect to the riparian species; thus, two homogeneous groups of species were identified: [JU, QC] and [SL, SP, SE, PN, SA]. In the case of the riparian species, the Huber estimator gave mean values of elevation quite similar to those given by the median and despite not appearing differences, a gradual pattern of species in relation to the elevation gradient was identified (SL: 1.1; SP: 1.2; SE: 1.3; PN: 1.4; SA: 1.5). The terrestrial species had a Huber estimator hovering around 5 m above thalweg. Looking at both groups, it is around 2 m above thalweg where the transition from riparian to terrestrial takes place.

2.5.2.2.3 Dominance curves

Most of the woody riparian species showed a clear suitability for a specific distance band in the riparian zone at Mijares-Terde (**Figure 2.22**). All of them, except for SE, showed their highest abundance values at the range 5-10 m to thalweg, being SP the dominant species, followed by PN. SE was more abundant in the range 0-5 m, but SP was the dominant species in that band as well. JU and QC showed their highest abundance values in the range 15-20 m to thalweg. A second peak of abundance was detected for SE and PN at that range as well. From that distance, the riparian species showed a decreasing trend and the terrestrial species increased their presence.

Regarding elevation above thalweg (**Figure 2.23**), all the riparian species except SA, showed their highest abundance values at the range 1-1.5 m above thalweg, where SP was the dominant species followed by PN. SA showed its highest abundance values at 0.5-1 m and it had a second peak in the range 2-2.5 m above thalweg. JU exhibited its highest abundance values at 3-3.5 m and again at 6-6.5 m. QC was more abundant at 2.5-3 m. From 3 m above thalweg and higher, the terrestrial species became dominant, with the exception of a small patch of PN located at 4.5-5 m.

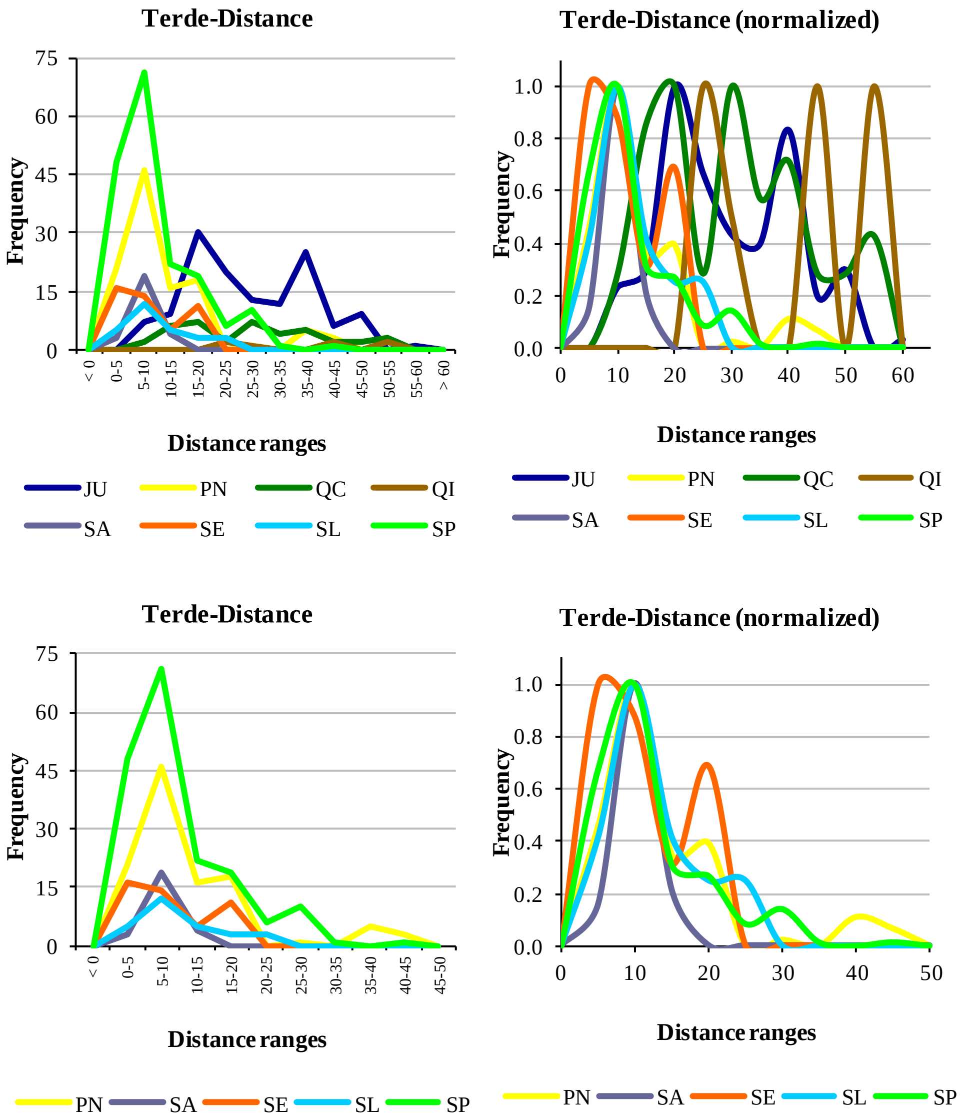


Figure 2.22. *Dominance curves respect to the distance to thalweg at the Mijares-Terde study reach. To improve the visualization, graphs on the top show all the species sampled at the reach and graphs on the bottom show only the riparian species.*

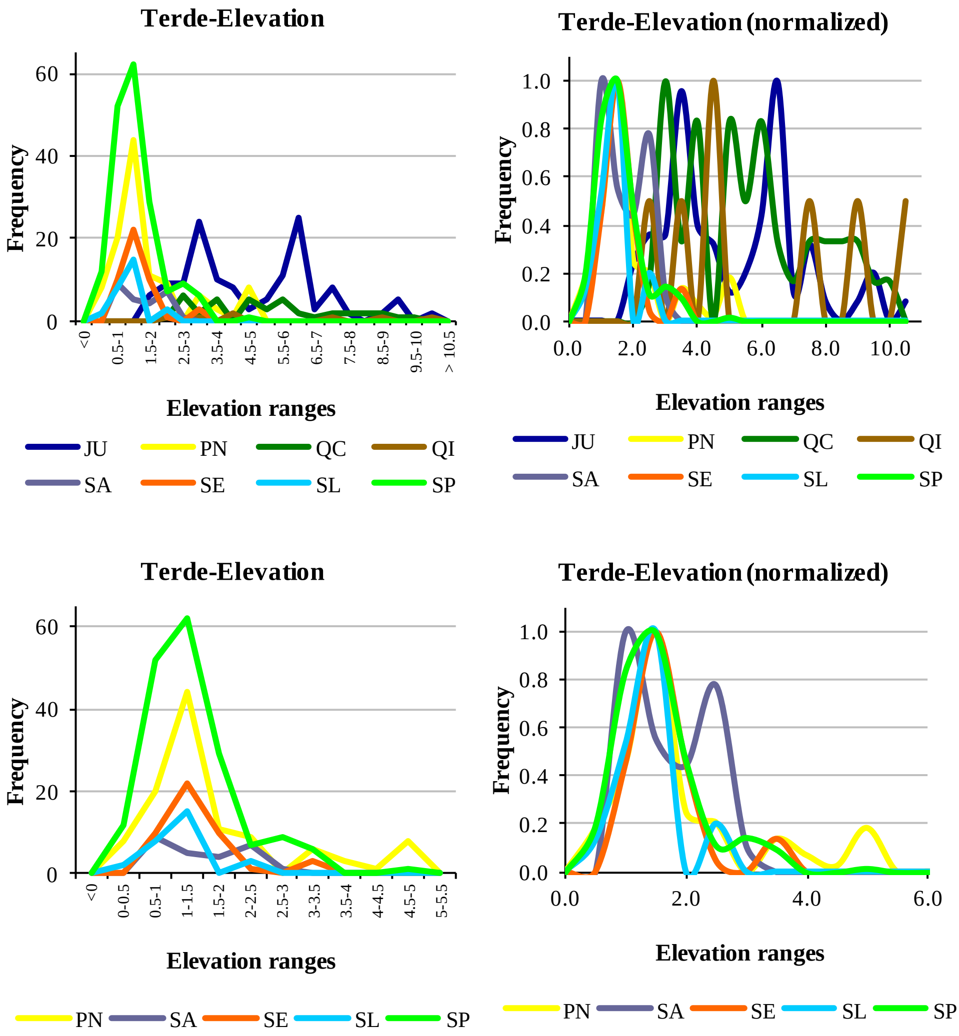


Figure 2.23. *Dominance curves respect to the elevation above thalweg at the Mijares-Terde study reach. To improve the visualization, graphs on the top show all the species sampled at the reach and graphs on the bottom show only the riparian species.*

2.5.2.2.4 Soil characteristics

Ten soil types were identified at Mijares-Terde study reach (**Figure 2.24**). The soils 2, 5, 8 and 10 had a quite similar coarse texture (gravel content equal or larger than 60 %). Soils 4, 6 and 7 were formed by sand and soils 1, 3 and 9 by sand and silt. Soil 6 was mainly sandy, but it had an equitable content of gravel, silt and clay. Apart from soil 6, soils 3 and 9 were the soils with the highest content of clay (> 10 %).

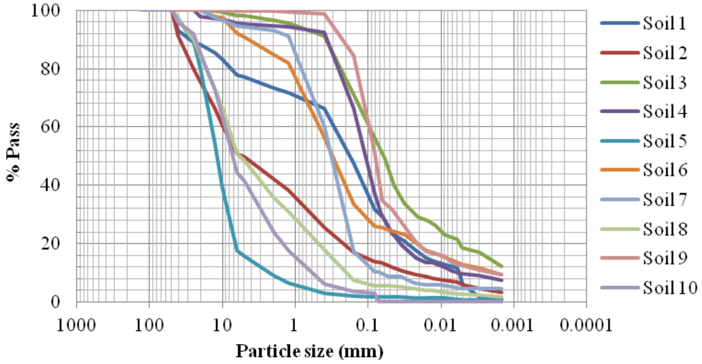


***Figure 2.24.** Grain size distribution of the soil samples of the Mijares-Terde study reach.*

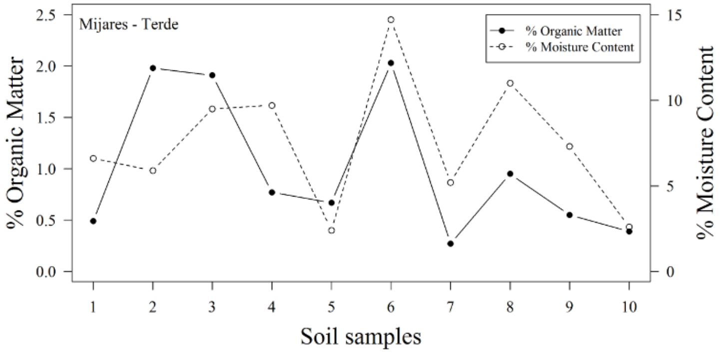


***Figure 2.25.** Percentages of organic matter and moisture content in the ten soil samples analyzed in the Mijares-Terde study reach.*

Regarding the organic matter content, soil 7 presented the lowest values (0.27 %) and soil 6 the highest ones (2.03 %). Furthermore, soil 6 presented the highest moisture content (14.70 %); the lowest moisture content (2.40 %) was presented by soil 5. In general, the soils with the lowest moisture content were those with coarser textures (**Figure 2.25**).

A decreasing trend in the gravel content was detected as we moved upwards in the elevation gradient (species in **Figure 2.26** and **Figure 2.27** appeared ordered according to the ranking defined by the Huber estimator for elevation above thalweg). The opposite, an increasing trend, was found for the other textures, except for sand where no clear trends were identified. In all cases, it was possible to identify visually the riparian and the terrestrial species as two different groups. QI was included in the graphs but it was not considered in the tests due to its small sample size.

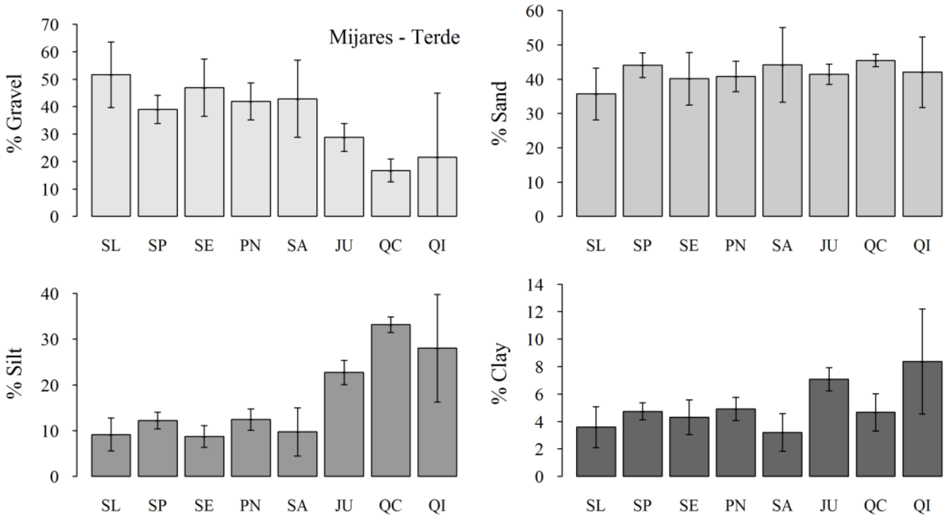


Figure 2.26. *Barplots with error bars for the percentage of gravel, sand, silt and clay for each species at the Mijares-Terde reach. The height of the bars represents the mean values and the whiskers represent the confidence interval for the standard error. Species appear in*

ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.

In relation to the gravel content (**Figure 2.26**) and considering all the species, significant differences ($FW_e = 9.26$; $p < 0.001$) were found. The test for multiple comparisons ($tr = 10$ %; $\alpha = 0.05$) revealed that QC had different proportions of gravel content in comparison with the rest of species, except for SA and JU. No differences were found among the riparian species (mean gravel content higher than 40 %). For the terrestrial species, the gravel content was lower than 30 %. Regarding the sand content, no significant differences were found among species ($FW_e = 1.96$; $p = 0.077$). Their mean values in sand content were between 36 % in the case of SL and 45 % in the case of QC.

With respect to the silt content, significant differences ($FW_e = 66.39$; $p = 0$) were detected. Three groups could be defined: the first group formed by the riparian species[SL, SP, SE, PN, SA] with 10 % as mean silt content; the second group formed by [JU] with 23 %; and the third group by [QC] with 33 %. Significant differences were detected in relation to the clay content as well at $tr = 10$ % and $\alpha = 0.05$ ($FW_e = 4.56$; $p < 0.001$), but these differences only occurred between JU (which had the highest mean clay value: 7 %) and the riparian species SA, SL and SP (mean clay content: 3-5 %).

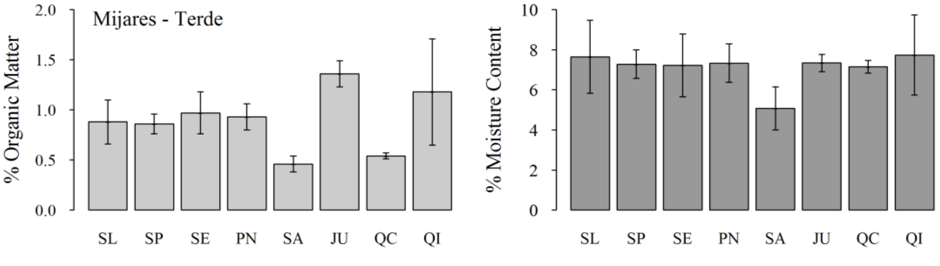


Figure 2.27. *Barplots with error bars for the percentage of organic matter and moisture content for each species at the Mijares-Terde reach. The height of the bar represents the mean value and the whiskers represent the confidence interval for the standard error. Species appear*

in ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.

In relation to the organic matter content (**Figure 2.27**), significant differences were found ($FW_e = 27.5$; $p = 0$) among the riparian species, specifically between SA (which showed the lowest values: 0.5 %) and PN, SE and SP (which had mean values hovering around 0.9 %). At the same time, JU showed differences with all the species (it presented the highest mean organic matter content: 1.4 %). Similarly, QC presented differences in comparison with PN and SP. In the case of the moisture content, significant differences were found among species ($FW_e = 2.46$; $p = 0.026$). However, these differences only took place between SA and JU, which had some of the highest and lowest mean values respectively (5.1 and 7.3 % of moisture content).

2.5.2.2.5 Multivariate interpretation

The species projections in the space defined by the first two components of the PCA (which explained 73.8 % of the total variance) corroborated, as detailed before, the clear separation between riparian (top of the plot) and proper terrestrial species (bottom) (**Figure 2.28**). The first axis, which explained 49.9 % of the variance, was positively related to CLAY (1.0), SILT (0.8), SM (0.8), and negatively to GRAVEL (-0.8). The second axis, which explained 23.8 % of the variance, was negatively related to both morphological variables, ELEV_THW (-0.9) and DIST_THW (-0.8), separating clearly both groups of species. They were also patent in the cluster and ordicluster respectively, performed on the coordinates of the first three PCA components, which explained 87.4 % of the total data variability (**Figure 2.29**). Riparian species were located closer to thalweg (both in distance and elevation) and in areas with a high gravel content. On the other hand, the proper terrestrial species (JU, QC and QI), although appearing as well in the riparian zone, were prone to appear in farther areas from the water's edge, characterized by a high silt content. Among the three of them, JU was located in areas with higher clay content respect to QC and QI. With regard to the riparian species, SA, SL and SP were located in areas with the lowest clay content.

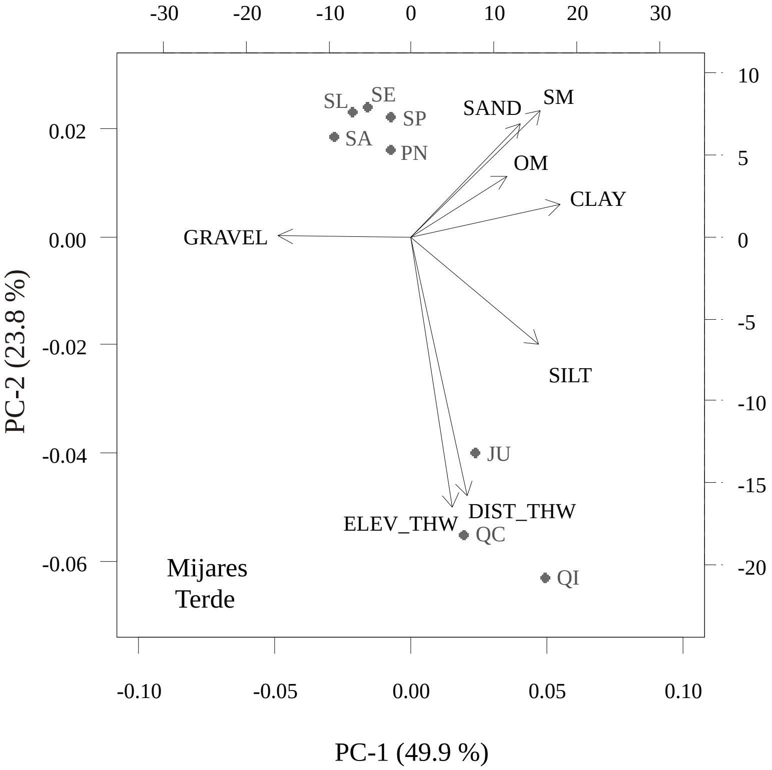


Figure 2.28. *PCA (principal components analysis) diagram for the Mijares-Terde study reach. Woody riparian species (dots in grey colour) are abbreviated as: SL, Salix alba L.; SP, Salix purpurea L.; PN, Populus nigra L.; SE, Salix eleagnos Scop.; SA, Salix atrocinerea Brot.; JU, Juniperus spp.; QC, Quercus coccifera L.; QI, Quercus ilex L.*

Within the riparian species, SA was revealed in the cluster and ordicluster as different from the rest. It was located in the outer limits of the riparian forest, in connection with the terrestrial vegetation. It showed lower organic matter content than the other riparian species but higher soil moisture than the terrestrial species. Therefore, considering the information given by the three analyses, two groups could be defined at the site MTE according to its river morphology and soil characteristics, as follows: [SE-SL-PN-SP-SA] and [QI-JU-QC]. Considering only the riparian species, two groups could be distinguished: [SA] and [SE-SL-SP-PN].

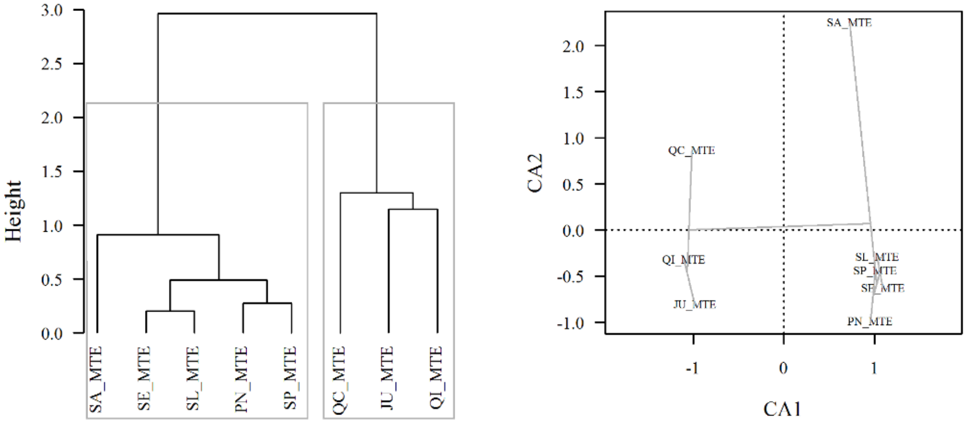


Figure 2.29. *Left plot, hierarchical cluster dendrogram (average clustering with Euclidean distance) based on the first three PCA scores for the woody riparian species recoded at the Mijares-Terde study reach. The vertical axis shows the level of fusion and is based on the dissimilarities between species. Right plot, clustering results overlaid onto an ordination diagram based on the proximity matrix. Cluster centroids are connected to each other with line segments similarly as in the original cluster dendrogram.*

2.5.2.3 Mijares – Cirat

2.5.2.3.1 Vegetation description

The number of transects surveyed at Mijares-Cirat was nine. Their mean length was 51 m and their range was from 39 m (the shortest transect) to 73 m (the longest one). The plant richness was seven (one tree species and six shrub species) (**Table 2.3**) and 107 was the total number of plants recorded. The total length of transects surveyed was 458 m and the length of plant cover 339 m, which depicted a total cover of woody riparian species of 74 % for the entire site. This is the lowest value of all the sites because its riparian zone was constrained by agricultural uses, its water surface was quite wide and furthermore, an important proportion of the site was covered by non-woody riparian species. For instance, common reed (*Phragmites australis*), giant reed (*Arundo donax*), rounded-headed club-rush (*Scirpus holoschoenus*), cattail (*Typha* spp.), etc., which were species not considered in this study.

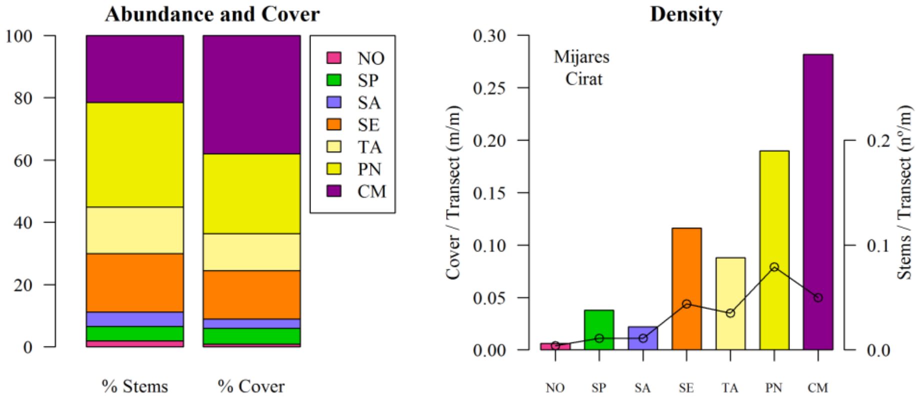


Figure 2.30. *Descriptors of the woody riparian species sampled by transects at the Mijares-Cirat study reach. Left plot shows abundance (percentage of stems of each species respect to the total number of plants sampled) and cover (percentage of cover of each species respect to the total cover value in the site). Right plot shows density (bars indicating meter of cover of each species per meter of transect, left axis; and points indicating number of stems of each species*

per meter of transect, secondary axis). Codes are noted in **Table 2.3***. Species appear in ascendant order according to the ranking defined by the Huber estimator in the elevation above thalweg.*

As can be seen in **Figure 2.30**, the most abundant species were *Populus nigra* (PN), *Coriaria myrtifolia* (CM), *Salix eleagnos* (SE) and *Tamarix* spp. (TA), with 34, 21, 19 and 15 % of the total number of stems, respectively. The rest of species, *Salix purpurea* (SP), *Salix atrocinerea* (SA) and *Nerium oleander* (NO) were less abundant (with 5, 5 and 2 % of stems).

In relation to cover, the pattern was different. CM showed the highest values (38 % of the total cover), followed by PN and SE (with 26 and 16 % of cover, respectively). All species showed lower values for cover than abundance, except in the case of CM, that presented patches formed by less stems than PN but they were more extensive. The other species exhibited more abundance of stems than cover in the site, revealing that they were growing and increasing their number of individuals in the site.

In relation to the density, CM showed the highest values (for each m of transect sampled, 0.3 m were covered by this species and additionally, this corresponded to 0.05 stems. However, PN showed the highest density of stems per m of transect (specifically, 0.08 stems/transect). SP, SA and NO showed low values for both, density of stems and cover. SE and TA presented intermediate values (around 0.35 stems and 0.1 m of cover per m of transect).

2.5.2.3.2 Distance and elevation above thalweg

The robust test of Welch gave a value of $FW\text{e} = 2.14$ ($p = 0.101$), therefore we accepted the null hypothesis of equal 0.1-trimmed means of distance to thalweg for all the species, but with caution (**Figure 2.31 – left**). As it is not always recommended to trim the data when the sample size is small, the non-parametric robust test of Kruskal-Wallis (designed by Rust and Fligner, 1984), hereafter K-W, was performed as well. It gave a value of 8.93 ($p = 0.111$), leaving no doubt in this case about the acceptance of the null hypothesis.

However, performing the same tests but excluding the species with the lowest sample sizes, i.e., SA and SP, the robust test of Welch gave a value of *FW*e = 2.73 (*p* = 0.059) at *tr* = 10 % and *FW*e = 3.39 (*p* = 0.034) at *tr* =20 %. In those conditions, the non-parametric robust test showed significant differences (K-W = 9.21; *p* = 0.026). Therefore, significant differences could be found depending on the data set and level of trimming considered.

The test for multiple comparisons showed no differences among species with a *tr* = 10 %, but with *tr* = 20 % some differences were found between CM and SP. Considering only those species with larger sample size, at *tr* = 20 % and α = 0.05, differences were found between CM and PN, CM and SE. This fact can be visually appreciated looking at the Huber estimator. CM had the highest value (13.8 m), followed by TA (10.4 m), whereas the rest of species exhibited values hovering around 8 and 9 m.

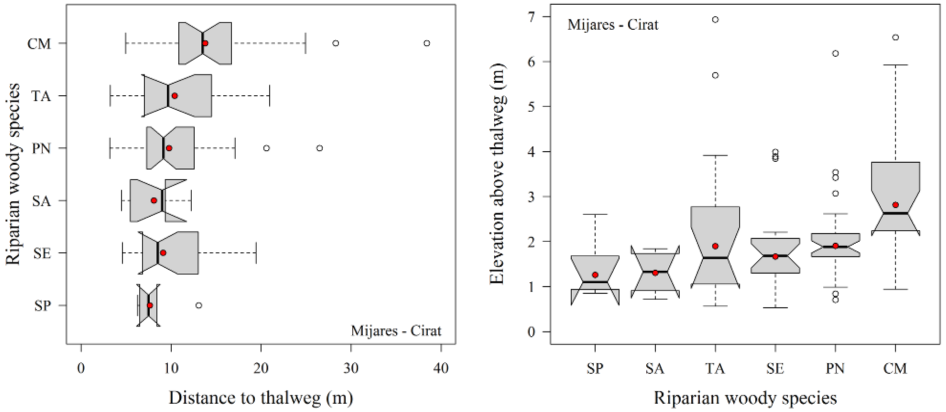


Figure 2.31. *Boxplots of the distribution (left plot - distance to thalweg; right plot-elevation above thalweg) of the woody riparian species sampled at the Mijares-Cirat study reach. Species are in ascendant order according to their median values. Red dots represent the Huber estimator.*

In elevation above thalweg (**Figure 2.31 – right**), the robust test of Welch gave a value of *FW*e = 3.99 (*p* = 0.011), therefore we rejected the null hypothesis of equal 0.1-trimmed means. In this case, the non-parametric robust test also significant (K-W = 18.92, $p = 0.002$). The test for multiple comparisons ($tr = 10$ % and $\alpha = 0.05$) showed significant differences in the elevations of CM respect to SA, but due to the small sample size of the later, we interpreted it with caution. However, considering the species with larger sample size and the same parameters for the test, significant differences were found between CM and PN, and CM and SE.

The Huber estimator gave mean values of elevation quite similar to those given by the median and showed a gradual pattern of species in relation to the elevation gradient (SP: 1.3; SA: 1.3; SE: 1.7; TA: 1.9; PN: 1.9; CM: 2.8). Looking at the whole picture drawn by these species, the three willows (SP, SA and SE) appeared closer and at the lowest elevations in the riparian zone; TA and PN occupied intermediate positions, having TA a wider distribution range in comparison with PN; and finally, CM appeared farther in distance and elevation above thalweg.

In the boxplots, NO was not shown due to its small sample size, but it deserves saying that two specimens appeared around 16 m distance and 2 m elevation above thalweg. The small sample size did not allow us to get conclusive results about this species, but its location could be assimilated to that shown by PN and CM.

2.5.2.3.3 Dominance curves

Woody riparian species found suitable habitats at a specific distance band in the riparian zone at Mijares-Cirat (**Figure 2.32**). All of them, except CM, showed their highest abundance values at the range 5-10 m to thalweg, being PN the dominant species, followed by SE. CM was more abundant in the range 10-15 m, but PN was the dominant species in that band as well. CM was dominant in the consecutive 5-m bands. The decreasing rate was at a much slower pace for TA than for the rest of the species.

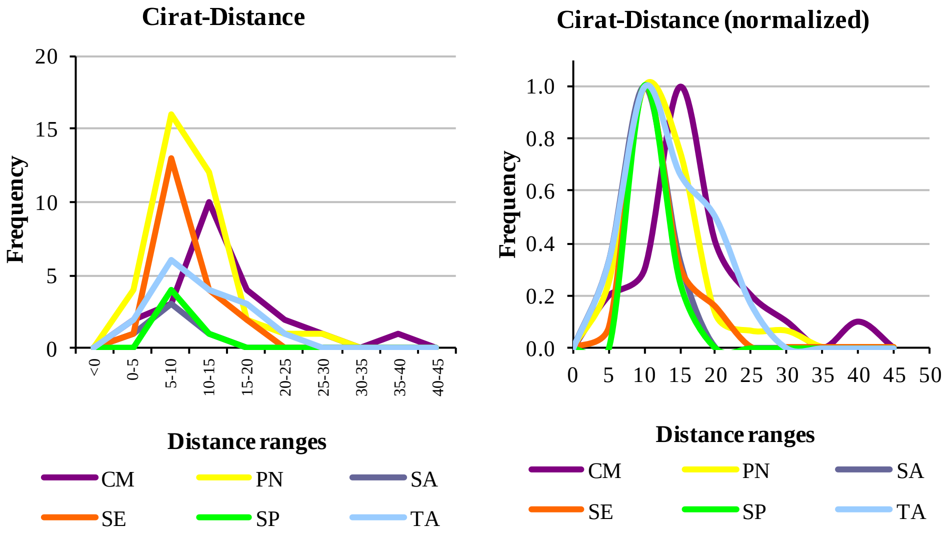


Figure 2.32. *Dominance curves of the woody riparian species respect to the distance to thalweg at the Mijares-Cirat study reach.*

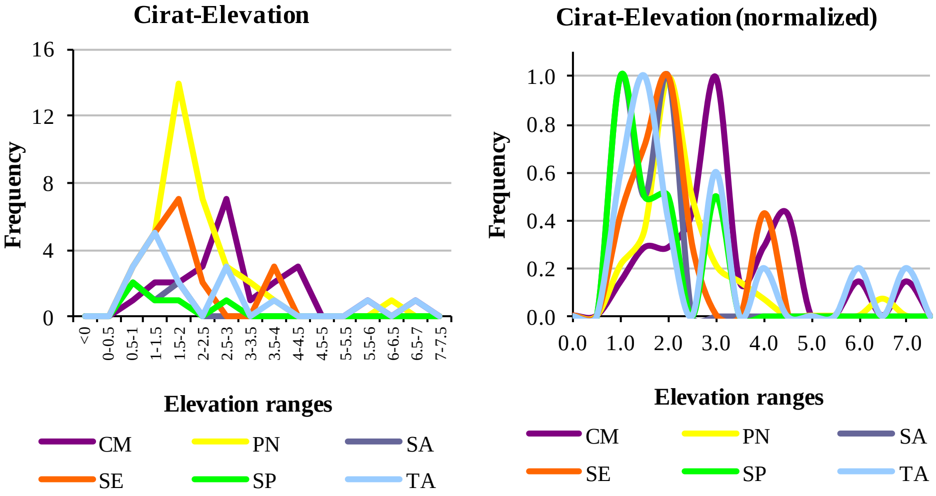


Figure 2.33. *Dominance curves of the woody riparian species respect to the elevation above thalweg at the Mijares-Cirat study reach.*

Regarding elevation above thalweg (**Figure 2.33**), species showed more differences in their dominance patterns. SP exhibited its highest abundance at the lowest elevations (band 0.5-1 above thalweg), however due to its small sample size, other species showed higher abundances at that range as well, such as PN, SE and TA. In the next band (1-1.5 m), TA showed its maximum abundance, but PN and SE were equally dominant in number. In the band 1.5-2 m above thalweg, PN was the dominant species and showed its highest abundance value, along with SE. Finally, CM showed its highest abundance and was dominant at the range 2.5-3 m above thalweg.

2.5.2.3.4 Soil characteristics

Six soil types were identified at Mijares-Cirat study reach. The soils 1, 2, 3 and 4 had a quite similar coarse texture (gravel content larger than 60 %). Soil 5 was formed by gravel and sand and soil 6 by sand and silt (**Figure 2.34**). The later had the highest content of clay of all the samples analysed (8 % in comparison to less than 2 % in the rest of them).

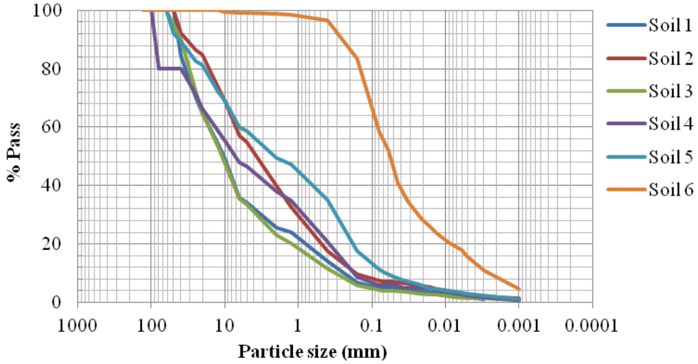


Figure 2.34. *Grain size distribution of the soil samples of the Mijares-Cirat study reach.*

With respect to the moisture content, it exhibited an identical pattern to the one showed by the percentage of clay. As mentioned before, soils 2 and 4 were very similar in texture; nevertheless, they differed in their percentage of organic matter and moisture (**Figure 2.35**). Soil 2 had high values for both of them parameters (2.55 % of organic matter and 5.7 % of moisture) and soil 4 showed the lowest values of all the samples (0.21 % of organic matter and 2.2 % of moisture). Soil 6 had the highest moisture content (9.1 %).

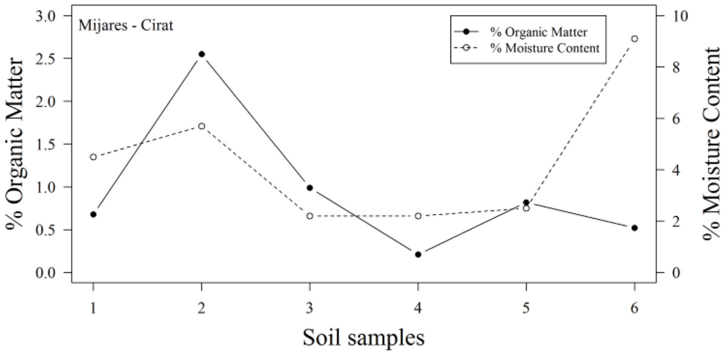


Figure 2.35. *Percentages of organic matter and moisture content in the six soil samples analyzed in the Mijares-Cirat study reach.*

In terms of soil suitability (**Figure 2.36**), no large differences were detected among species. A small decreasing trend in the gravel content was detected as we moved upwards in the elevation gradient (species in **Figure 2.36** and **Figure 2.37** appear ordered according to the ranking defined by the Huber estimator for elevation above thalweg). The opposite, an increasing trend, was found for the other textures. In all cases, SA was related to the minimum mean values, except for the gravel content. Nevertheless, no significant differences were found among species using *tr* = 10 % for a specific gravel content in the soil. Regarding the sand content, no significant differences were detected among species with any of the two tests. SA showed the lowest mean value (22 % of sand). For the rest of species, the sand content was close to 30 %.

The robust ANOVA of Welch (*tr* = 10 %; α = 0.05) showed the same results as the K-W test. With *tr* = 20 %, significance differences were detected for the gravel and sand content, in the most far apart species, normally SA and CM.

The lack of differences between species could be a consequence of the small sample size and the homogeneity detected in the soil characteristics of this site.

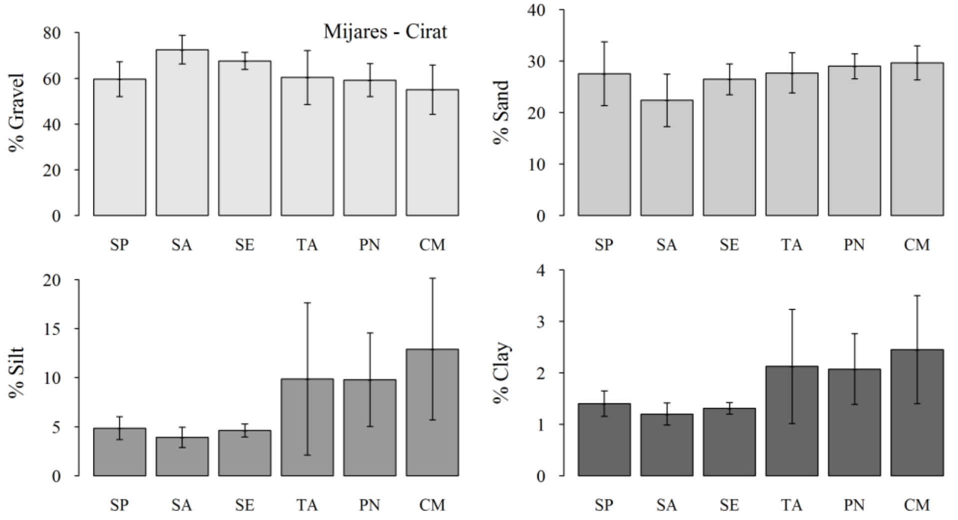


Figure 2.36. *Barplots with error bars for the percentage of gravel, sand, silt and clay for each species at the Mijares-Cirat study reach. The height of the bars represents the mean values and the whiskers represent the confidence interval for the standard error. Species appear in ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.*

With respect to the silt content, no differences were detected neither ($FW_e = 0.69$; $p = 0.633$). The mean content of silt for all the species was hovering around 5 and 15 % (median value = 5 %), but a larger variation was noted by TA, PN and CM than for SP, SA and SE.

In all the samples, the content of clay was very small, so no clear differences existed among different parts of the riparian zone and hence, among the suitability for the riparian species. The pattern observed for the clay was similar to the one observed by the silt content, i.e., the mean content of clay for all the species was hovering around 1.2 and 2.5 %, but a larger variation was noted for TA, PN and CM than for SP, SA and SE.

Similarly, no differences appeared among species in relation to the organic matter (*FW*e = 1.16; *p* = 0.360) and moisture content (*FW*e = 0.61; *p* = 0.689). A decreasing trend was detected in the case of the organic matter along the elevation gradient, but no trends appeared in the moisture content. TA got the lowest mean value of organic matter (0.8 %) and SP the highest mean values for both parameters (1.9 % of organic matter and 4.8 % of moisture content).

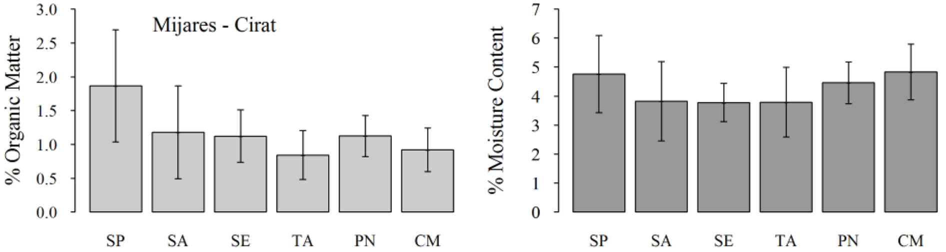


Figure 2.37. *Barplots with error bars for the percentage of organic matter and moisture content for each species at the Mijares-Cirat study reach. The height of the bar represents the mean value and the whiskers represent the confidence interval for the standard error. Species appear in ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.*

2.5.2.3.5 Multivariate interpretation

The first two components of the PCA explained 75.9 % of the total variance (**Figure 2.38**). The first axis summarized most of this percentage (58.9 %) and was positively related to GRAVEL (1.0), and negatively related to SILT (-0.9), CLAY (-0.9), SAND (-0.8), SM (-0.8) and DIST_THW (-0.7), what suggests that the transverse gradient was defined by high gravel content near the water's edge and an increasing content in fine substrate and soil moisture as we moved upslope). The second axis explained 17.0 % of the variance and was positively related to OM (0.7) and negatively to ELEV_THW (-0.7).

The cluster and ordicluster explained 90.0 % of the total data variability (**Figure 2.39**). Although there was a relevant overlap between species (as shown in **Figure 2.31**) and no significant differences were found in soil suitability, the multivariate analysis allowed us to interpret the positional patterns of each species and their associations with the physical variables.

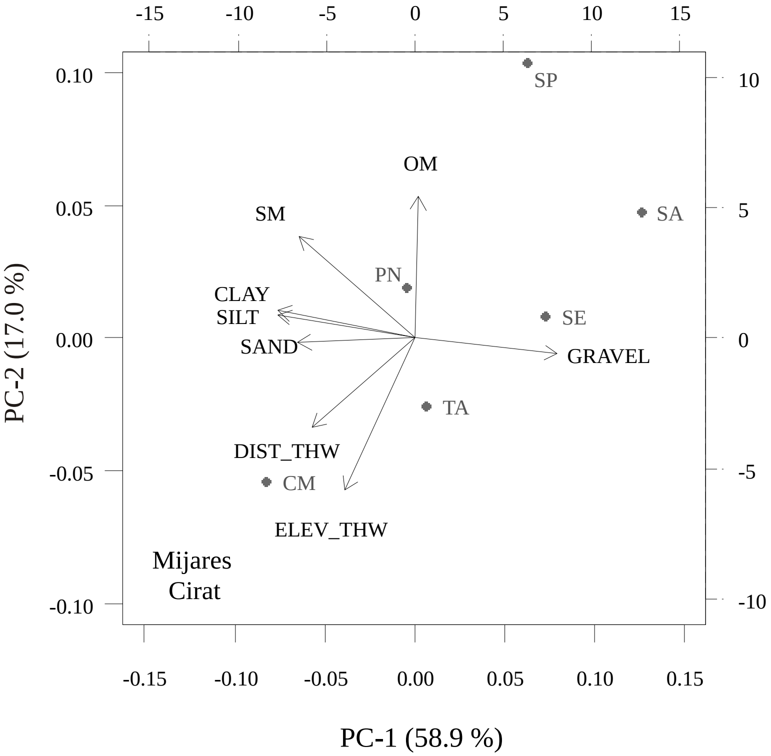


Figure 2.38. *PCA (principal components analysis) diagram for the Mijares-Cirat study reach. Woody riparian species (dots in grey colour) are abbreviated as: SP, Salix purpurea L.; PN, Populus nigra L.; SE, Salix eleagnos Scop.; SA, Salix atrocinerea Brot.; CM, Coriaria myrtifolia L.; TA, Tamarix spp.*

The three species from the genus *Salix* (SP, SA and SE) were located close to thalweg and were grouped in one branch of the cluster and in the right side of the ordicluster. Between them, SP was the species appearing closest in distance and elevation to/above thalweg and was associated with high organic matter content. SA was in the areas with the coarsest substrate (high gravel content). TA and PN appeared in intermediate positions, characterized by fine substrate, but TA was located in areas with lower organic matter content and soil moisture than PN. CM was the species appearing in areas with the finest substrate and farther from thalweg, although it was the species with the widest distribution range.

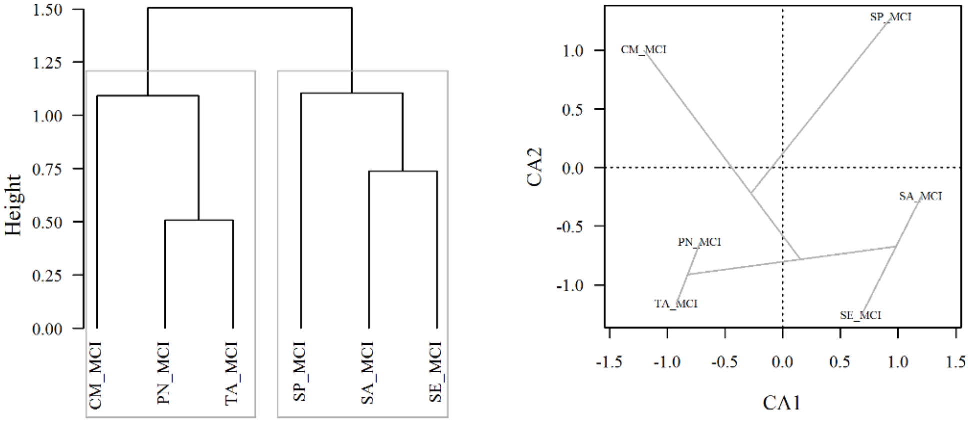


Figure 2.39. *Left plot, hierarchical cluster dendrogram (average clustering with Euclidean distance) based on the first three PCA scores for the woody riparian species recorded at the Mijares-Cirat study reach. The vertical axis shows the level of fusion and is based on the dissimilarities between species. Right plot, clustering results overlaid onto an ordination diagram based on the proximity matrix. Cluster centroids are connected to each other with line segments similarly as in the original cluster dendrogram.*

The ordicluster showed clearly two homogeneous groups formed by PN-TA and SA-SE, as well as the cluster. Therefore, four groups could be defined in MCI, as follows: [PN-TA], [CM], [SE-SA], [SP]. Due to the small sample size of some of these species, just two groups could be defined, formed by [SP-SA-SE], [TA-PN-CM]. The first group would appear mainly in the bank zone, characterized by coarse substrate and high organic matter content. The second group would appear in the floodplain zone, farther from the thalweg in distance and elevation, and would be related with soils of fine texture, low organic matter content and high soil moisture.

2.5.2.4 Mijares – Tormo

2.5.2.4.1 Vegetation description

The number of transects surveyed at Mijares-Tormo was nine. Their mean length was 46 m and their range was from 29 m (the shortest transect) to 66 m (the longest one). The plant richness was seven (one tree species and six shrub species) (**Table 2.3**) and 133 was the total number of plants recorded. The total length of transects surveyed was 411 m and the length of plant cover 400 m, which depicted a total cover of 97 % for the entire site. There were some areas uncovered, those were bedrock was the main substrate, but a more or less constant shrub layer was present in the rest of the site. In particular, transects revealed that 88 % of the total cover in the site was formed by shrub species.

As can be seen in **Figure 2.40**, the most abundant species were *Nerium oleander* (NO) and *Coriaria myrtifolia* (CM), with 27 % and 17 % of the total number of stems, respectively, indicating that the corridor was characterized by a shrubby riparian forest. *Populus nigra* (PN), *Salix eleagnos* (SE), *Tamarix* spp. (TA) and *Viburnum tinus* (VT) followed in abundance the former species, with a equitable percentage of stems among them (13-14 %), whereas *Salix atrocinerea* (SA) showed the lowest values, just 2 % of stems (sample size = 3 stems).

In contrast to the abundance, the cover showed a different pattern, with CM having the highest values (31 % of the total cover) and followed by NO and TA (with 19 and 18 % of cover, respectively). In the case of TA and CM, the values for cover were larger than those for abundance. This meant that these species presented old and big specimens, in the case of the TA, and a few but very extensive patches of bush of CM. VT showed an opposite pattern respect to TA and CM, i.e., it exhibited more abundance of stems than cover in the site, revealing that it was an species growing and increasing its number of individuals in the site.

In relation to the density, CM showed the highest values (for each m of transect sampled, 0.3 m were covered by this species and additionally, this corresponded to 0.05 stems. However, NO showed the highest density of stems per m of transect (specifically, 0.09 stems/transect). The rest of species, except for SA, showed a density of stems per transect slightly lower than that showed by CM. Complementary, both NO and TA were characterized by around 0.18 m of cover per m of transect, but the density of stems of NO was double than that showed by TA. SE and VT had a density lower than 0.1 m of cover per m of transect. Finally, SA was the species less abundant in the site and it presented the lowest values of density as well, however the values of cover were slightly higher than the values of abundance, evidencing that the specimens albeit scarce were of large size.

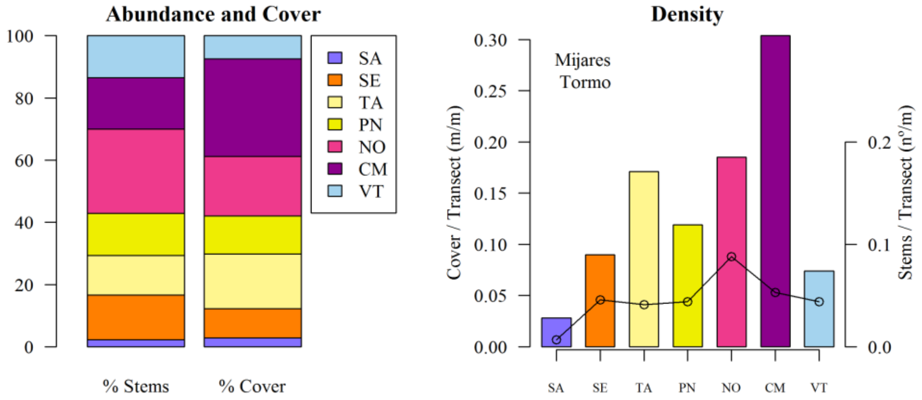


Figure 2.40. *Descriptors of the woody riparian species sampled by transects at the Mijares-Tormo study reach. Left plot shows abundance (percentage of stems of each species respect to the total number of plants sampled) and cover (percentage of cover of each species respect to the total cover value in the site). Right plot shows density (bars indicating meter of cover of each species per meter of transect, left axis; and points indicating number of stems of each species per meter of transect, secondary axis). Codes are noted in* ***Table 2.3****. Species appear in ascendant order according to the ranking defined by the Huber estimator in the elevation above thalweg (except for SA).*

2.5.2.4.2 Distance and elevation above thalweg

Differences in the positional pattern of the riparian species at Mijares-Tormo were detected in relation to the elevation but not to the distance to thalweg. The robust test of Welch gave a value of $FWe = 2.18$ ($p = 0.072$), therefore we accepted the null hypothesis of equal 0.1-trimmed means of distance to thalweg for all the species, but with caution (**Figure 2.41 – left**). As it is not always recommended to trim the data when the sample size is small, the K-W test was implemented as well, leaving no doubt in this case about the acceptance of the null hypothesis. Therefore, no differences were found in relation to the distance of the species to thalweg at Mijares-Tormo study reach. As illustrated by the Huber estimator, only SE seemed to appear closer to thalweg. It gave a value of 6.5, whereas the rest of species showed values hovering around 9 and 10 m.

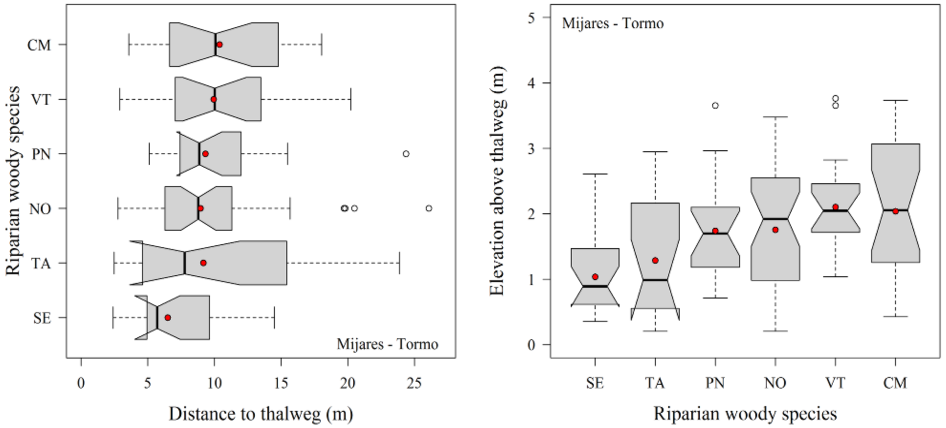


Figure 2.41. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the woody riparian species sampled at the Mijares-Tormo study reach. Species are in ascendant order according to their median values. Red dots represent the Huber estimator.*

In relation to the elevation above thalweg (**Figure 2.41 – right**), the robust test of Welch gave a value of $FWe = 4.69$ ($p = 0.001$), therefore we rejected the null hypothesis of equal 0.1-trimmed means. In this case, the K-W test rejected the null hypothesis even clearly ($p = 0.0005$). The test for multiple comparisons ($tr = 10$ % and $\alpha = 0.05$) showed significant differences in the elevations of SE respect to CM and VT, which were the most far apart species in the elevation gradient. Considering $tr = 20$ % and 0.05 or 0.10 as significance levels, only significant differences were found between SE and VT, underpinning the result obtained in the distance to thalweg and evidencing SE as a species with a different behavior in comparison with the rest of species. In this case, the Huber estimator gave mean values of elevation slightly different as those given by the median and showed a more gradual pattern of species in relation to the elevation gradient (SE: 1; TA: 1.3; PN: 1.7; NO: 1.8; CM: 2.0; VT: 2.1). This ranking was used to present the patterns of soil properties.

SA was not shown in the boxplots due to its small sample size, but it deserves saying that two specimens of this species appeared located around 5 m distance and 2 m elevation above thalweg, and the third specimen at 19 m distance and 5 m elevation. They were old specimens located on the right bank of the first transects. The small sample size did not allow us to get conclusive results about this species.

2.5.2.4.3 Dominance curves

As can be seen in **Figure 2.42**, the results at Mijares-Tormo showed a clear location in a specific distance band in the riparian zone. SE and TA were the species appearing closer to thalweg and exhibited dominance for that specific location. Nevertheless, all the species showed the highest abundance in the range 5-10 m to thalweg.

At that location, NO was the dominant species. From that distance (10 m), all species presented a decreasing trend, except for VT, which selected the range 10-15 m. NO and CM showed high values of abundance in that range as well, but their decreasing trend was at a much slower pace than in the rest of species.

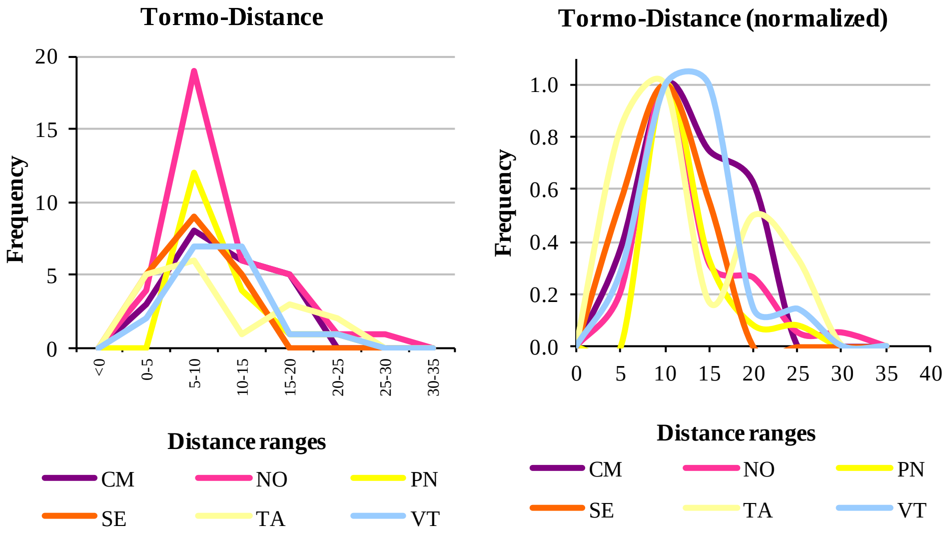


Figure 2.42. *Dominance curves of the riparian species respect to the distance to thalweg at the Mijares-Tormo study reach.*

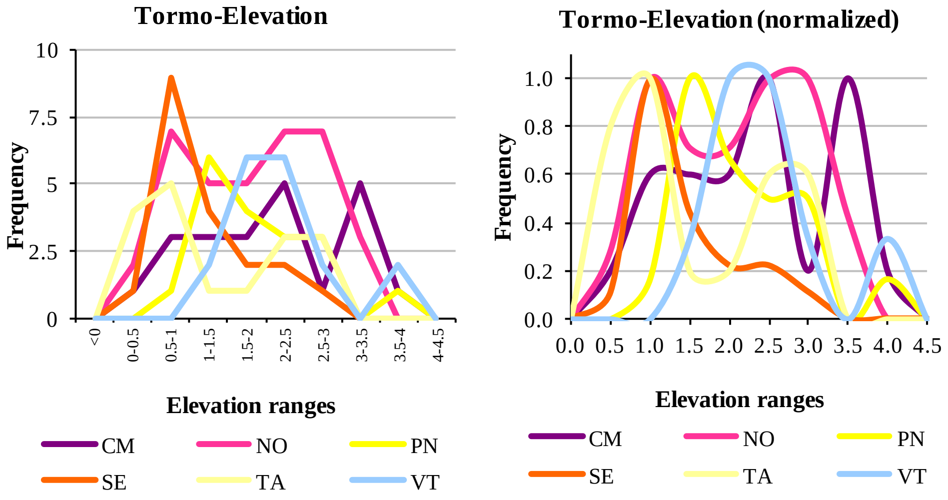


Figure 2.43. *Dominance curves of the riparian species respect to the elevation above thalweg at the Mijares-Tormo study reach.*

In relation to elevation above thalweg (**Figure 2.43**), species showed higher differences than in relation to the distance to thalweg. TA was dominant at low elevations (0-0.5 m above thalweg), followed by SE and NO in the next range (0.5-1 m). SE was dominant at that range and it showed a narrow distribution, showing a sharp drop from 1.5 m. By contrast, NO presented a steady abundance over the entire elevation gradient. PN was the dominant species in 1-1.5 m and its decline was gradual from that elevation. In the next range (1.5-2 m), VT was the dominant species, accompanied by NO and CM in the next range. Finally, CM was the dominant species at the highest elevations.

2.5.2.4.4 Soil characteristics

Only four soil types were identified, in relation with the short length of this site. For the first three soils, a sample was analysed. A fourth soil type was assigned to the areas covered with bedrock and no soil sample was taken. The three soil samples differed in their grain size distribution (**Figure 2.44**). Soils 2 and 3 had a coarse texture (gravel content of 78 and 67 %, respectively), but soil 3 had less sand and more silt than soil 2. Soil 1 was mostly composed by sand (76 %) and it had the highest content of clay of the three soils (6 %, respect to 1 % of soils 2 and 3).

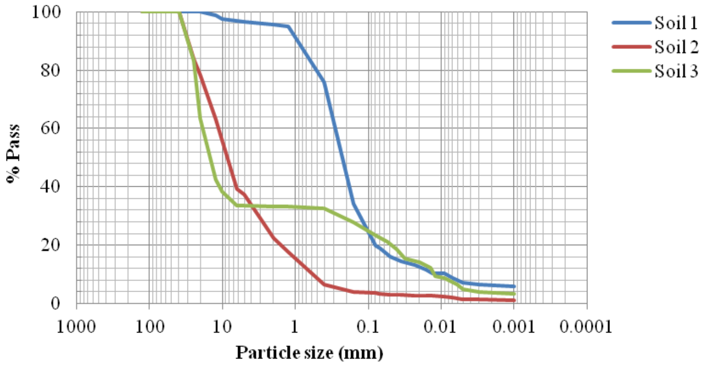


Figure 2.44. *Grain size distribution of the soil samples of the Mijares-Tormo study reach.*

Regarding the organic matter and moisture content (**Figure 2.45**), soil 1 showed the lowest values (1.25 %), but on the contrary, it showed the highest moisture content (approx. 10 %). Soil 3 was the opposite (the largest organic matter and the lowest moisture content; 4.24 % and 2.9 %, respectively). Soil 2 exhibited intermediate values of moisture and low organic matter content, similarly to soil 1.

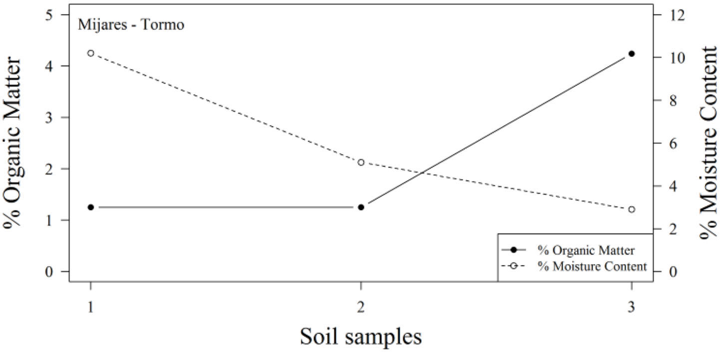


Figure 2.45. *Percentages of organic matter and moisture content in the three soil samples analyzed in the Mijares-Tormo study reach.*

In terms of soil patterns (**Figure 2.46**), a general trend was identified. Considering the species ordered according to the ranking defined by the Huber estimator for elevation above thalweg, as we move upwards in the elevation gradient, a decreasing trend was found in the gravel content and an increasing trend in the sand, silt and clay content.

In the case of the gravel content, significant differences were found among species ($F_{We} = 5.94$; $p < 0.001$) using $tr = 10$ %. The test for multiple comparisons (performed as well using $tr = 10$ % and $\alpha = 0.05$), indicated differences between TA and VT, which were the species located in the places with the highest (68 %) and lowest (37 %) mean gravel content, respectively, although SE had the highest median value (78 %). SE, TA and PN had smaller standard deviation than NO, CM and VT, evidencing a clear preference of the former species for soils of coarse texture.

Regarding the sand content, significant differences ($FW_e = 5.63$; $p < 0.001$) were detected between TA-CM and between TA-VT. Specifically, TA showed the lowest preference for sand (19 %), whereas CM and VT showed the highest (42 and 44 %, respectively). In relation to the median values, all species had a preference of 19 %, except for VT, which had 47 %.

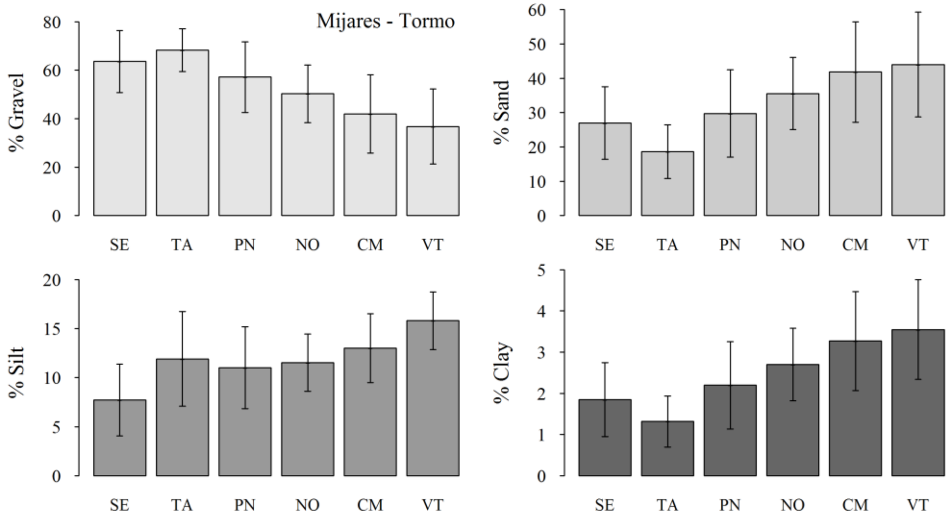


Figure 2.46. *Barplots with error bars for the percentage of gravel, sand, silt and clay for each species at the Mijares-Tormo study reach. The height of the bars represents the mean values and the whiskers represent the confidence interval for the standard error. Species appear in ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.*

The ANOVA of Welch revealed no significant differences among species ($FW_e = 2.30$; $p = 0.06$) in relation to the silt content. However, the p was close to the rejection of the null hypothesis, then the test for multiple comparisons was performed. Using $tr = 10$ % and $\alpha = 0.05$, it showed differences between SE and VT, as consequence of having the lowest and highest mean values of silt in their locations (8 and 16 %, respectively). With the same test parameters, differences were found between TA and VT respect to the clay content. VT was located further apart from the thalweg, and hence, in soils with the finest texture.

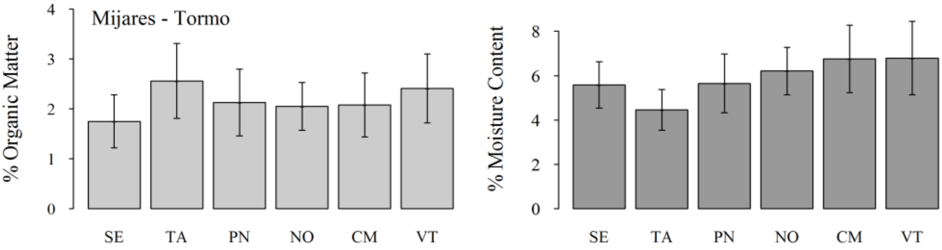


Figure 2.47. *Barplots with error bars for the percentage of organic matter and moisture content for each species at the Mijares-Tormo study reach. The height of the bar represents the mean value and the whiskers represent the confidence interval for the standard error. Species appear in ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.*

As can be seen in **Figure 2.47**, no significant differences were found in relation to the organic matter content ($FW_e = 0.76$; $p = 0.585$). The median value for all the species was 1.25 %. SE appeared to have the lowest mean values, and TA and VT the highest, but in any case, it was higher than 2.5 %. In contrast to this, slight differences were found in the moisture content ($FW_e = 3.45$; $p = 0.010$). These took place between TA and the rest of species. However, no differences were detected in their median values; all of the species appeared in locations with a soil moisture of 5.10 %, except for VT, which had 7.65 %. This was corroborated by our observations in the field, as most of the VT were located in fresh and shady places.

Overall, 13 plants appeared located on soil type 4 and they were not included in the two previous graphs, as no soil parameters were determined in that soil type. NO supposed 46 % of the plants in this soil type and 31 % was represented by CM. PN, SE and TA composed the rest 23 %.

2.5.2.4.5 Multivariate interpretation

The following analyses allowed us to define riparian groups at the Mijares-Tormo (MTO) study reach. The first two axes of the PCA explained 80.7 % of the data variability (**Figure 2.48**). The first axis (which explained 46.9 %), was positively related to GRAVEL (0.8) and negatively to SAND (-1.0), CLAY (-1.0) and SM (-0.9), defining a gradient in the soil conditions. The second axis (which explained 33.9 % of the variance), was negatively related to SILT (-0.9), OM (-0.9), DIST_THW (-0.8) and ELEV_THW (-0.7).

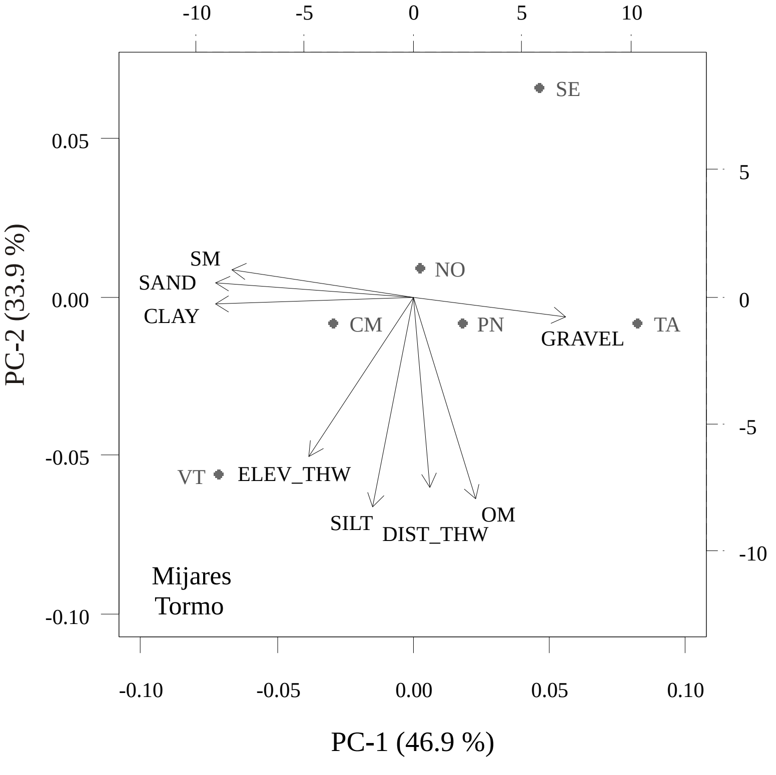


Figure 2.48. *PCA (principal components analysis) diagram for the Mijares-Tormo study reach. Woody riparian species (dots in grey colour) are abbreviated as: SE, Salix eleagnos Scop.; Populus nigra L.; Nerium oleander L.; Coriaria myrtifolia L.; Tamarix spp.; Viburnum tinus L.*

The species projection in the space defined by the first two components of the PCA allowed us interpreting the groups obtained from the cluster and ordicluster, which were performed on the coordinates of the first three PCA components, that accounted for 92 % of the data variability (**Figure 2.49**).

SE and TA were located in the bank zone, close to thalweg in distance and elevation, in areas characterized by coarse substrate and low soil moisture. Both species appeared as a distinct group in both, cluster and ordicluster. NO and PN appeared as part of the new group, a little farther from thalweg, in areas with a variety of substrates from those with fine texture to bedrock. CM occupied similar areas, but it was located in soils with finer texture and higher soil moisture than NO and PN. VT appeared associated to the farthest areas to thalweg with the finest substrate but with higher organic matter and soil moisture content than CM. Taking all of this into consideration, three riparian groups could be defined at the MTO according to its river morphology and soil characteristics, as follows: [SE-TA], [NO-PN-CM], [VT].

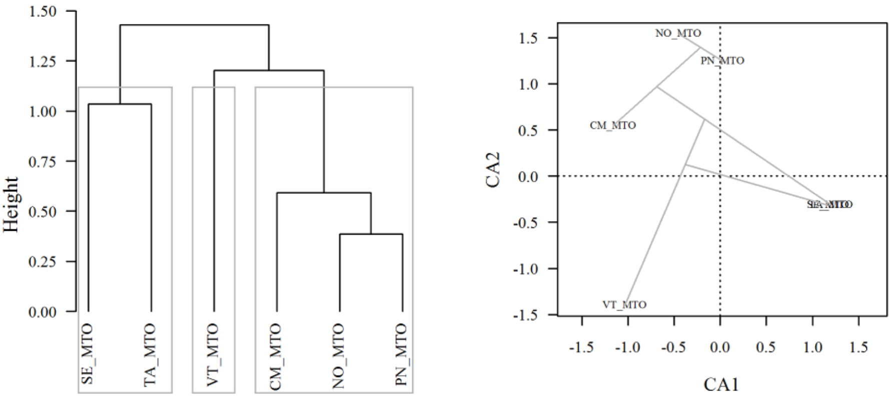


Figure 2.49. *Left plot, hierarchical cluster dendrogram (average clustering with Euclidean distance) based on the first three PCA scores for the woody riparian species recorded at the Mijares-Tormo study reach. The vertical axis shows the level of fusion and is based on the dissimilarities between species. Right plot, clustering results overlaid onto an ordination diagram based on the proximity matrix. Cluster centroids are connected to each other with line segments similarly as in the original cluster dendrogram.*

2.5.2.5 Serpis – Lorcha

2.5.2.5.1 Vegetation description

Eleven transects were surveyed at the Serpis-Lorcha study reach. Their mean length was 59 m and their range was from 44 m (the shortest transect) to 70 m (the longest one). The plant richness was six (two tree species and four shrub species) (**Table 2.3**) and 206 was the total number of plants recorded. The total length of transects surveyed was 649 m and the length of plant cover was 469 m, which depicted a total cover of 72 % for the entire site (56 % formed by shrubs and 44 % by trees). There were some areas uncovered, part of the water surface and those areas were bedrock was the main substrate. The rest was covered by non-woody species (mainly grass and reed).

Regarding the abundance (**Figure 2.50**), *Nerium oleander* (NO), *Populus nigra* (PN) and *Salix atrocinerea* (SA) were the most abundant species, with 30, 21 and 20 % of the total number of stems, respectively. These were followed by *Populus alba* (PA; 16 %) and *Crataegus monogyna* (CR; 11 %). Finally, *Viburnum tinus* (VT) presented the lowest abundance values (2 % of stems; N = 4).

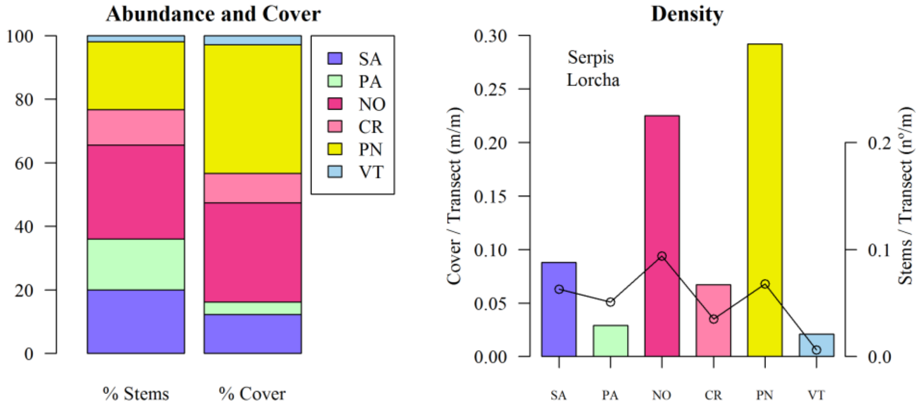


Figure 2.50. *Descriptors of the woody riparian species sampled by transects at the Serpis-Lorcha study reach. Left plot shows abundance (percentage of stems of each species respect to*

the total number of plants sampled) and cover (percentage of cover of each species respect to the total cover value in the site). Right plot shows density (bars indicating meter of cover of each species per meter of transect, left axis; and points indicating number of stems of each species per meter of transect, secondary axis). Codes are noted in ***Table 2.3****. Species appear in ascendant order according to the ranking defined by the Huber estimator in the elevation above thalweg.*

With respect to cover, PN showed the highest values (40 %), followed by NO (31 %), values both of them larger than those presented for abundance. This meant that these species presented old and big specimens (with more emphasis in the case of PN). In contrast, PA and SA showed the opposite pattern, with smaller values of cover than abundance (PA: 4 %; SA: 12 %), suggesting that both species were mainly represented by young individuals.

In relation to the density, PN showed the highest values (for each m of transect sampled, 0.3 m were covered by this species and additionally, this corresponded to 0.07 stems/m). However, NO showed the highest density of stems per m of transect (specifically, 0.09 stems/transect) and followed PN in density of cover (0.23 m/m). The rest of species showed values of cover lower than 0.10 m/m, presenting SA and CR values slightly higher than PA and VT. However, the density of stems of SA (0.06 stems/m) was higher than the density showed by PA and CR (0.05 and 0.04 stems/m, respectively). VT showed lowest values for both, density of cover and stems.

2.5.2.5.2 Distance and elevation above thalweg

The null hypothesis was rejected for equal 0.1-trimmed means ($FWe = 79.32$; $p = 0$) of distance to thalweg for all the species (**Figure 2.51 – left**). The test for multiple comparisons with a $tr = 10$ % and $\alpha = 0.05$ showed four groups of species: [PA],[SA],[NO] and [PN-CR], i.e., all the species showed a different positional pattern in relation to distance to thalweg, except for PN and CR. However, three groups could be defined using 0.10 as significance level, these were: [PA], [SA] and [NO-PN-CR]. These three groups of species can be visually appreciated looking at the Huber estimator. PA had the lowest value

(4.7 m), followed by SA (12.4 m) and NO (17.7 m), whereas PN and CR exhibited values hovering around 22 m. VT might have been included in this third group according to its Huber estimator (26 m) but its low sample size did not allow us including it in the tests.

In relation to the elevation above thalweg (**Figure 2.51 – right**), the robust test of Welch gave a value of $FW_e = 73.21$ ($p = 0$), therefore we rejected the null hypothesis of equal 0.1-trimmed means. The test for multiple comparisons ($tr = 10$ % and $\alpha = 0.05$) showed significant differences among all the species, except for CR-NO and CR-PN, hence the following groups of species could be defined in relation to their elevation above thalweg: [SA], [PA], [NO-CR] and [CR-PN]. The same results were obtained using 0.10 as significance level. The Huber estimator gave mean values of elevation quite similar to those given by the median and showed a gradual pattern of species in relation to the elevation gradient (SA: 1.0; PA: 1.4; NO: 1.9; CR: 2.1; PN: 2.3; VT: 2.6).

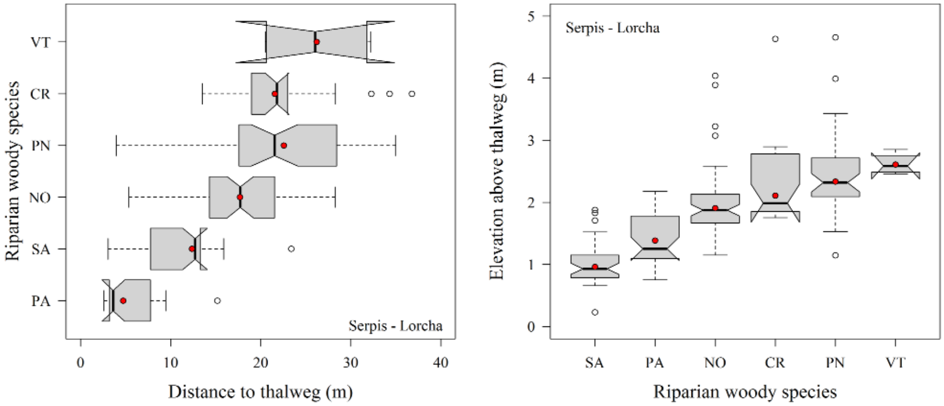


Figure 2.51. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the woody riparian species sampled at the Serpis-Lorcha study reach. Species are in ascendant order according to their median values. Red dots represent the Huber estimator.*

As can be seen, comparing both boxplots, the species were organized in different order in relation to distance and elevation above thalweg. PA was the closest species in distance and SA in elevation above thalweg. VT appeared always in the most far apart places, especially in the left bank under the canopy of the big specimens of PN, which was the species with the highest dispersion of individuals across the entire floodplain width. In any case, SA and PA were the species appearing in a first riparian line, closer to the water's edge, and NO, PN and CR in a second line slightly far and elevated respect to the water's edge.

2.5.2.5.3 Dominance curves

Woody riparian species showed a clear pattern at specific distance band in the riparian zone (**Figure 2.52**).

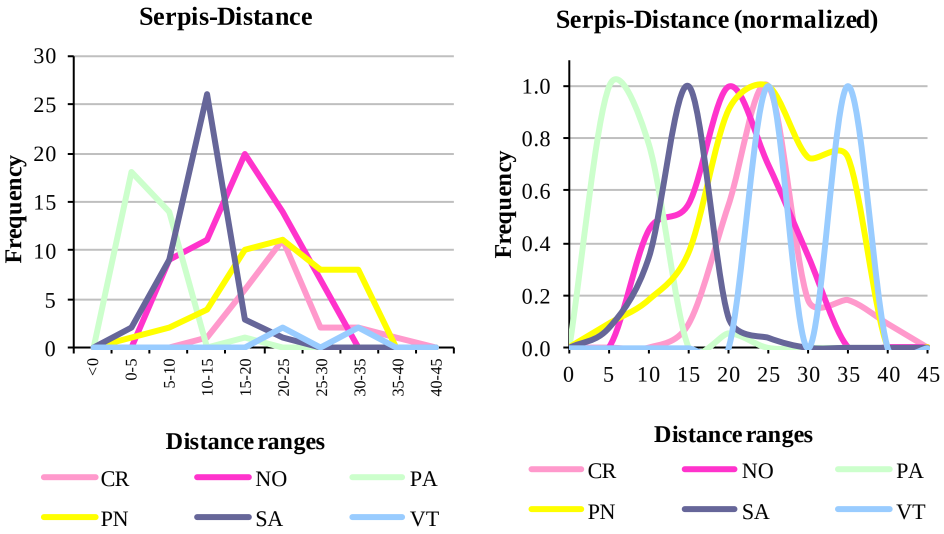


Figure 2.52. *Dominance curves of the riparian species respect to the distance to thalweg at the Serpis-Lorcha study reach.*

PA was the dominant and more abundant species in the range 0-5 m to thalweg. PA was dominant as well in the next range (5-10 m to thalweg), followed by SA and NO. SA showed its dominance in the range 10-15 m and was the most abundant species at that range as well. On the other hand, NO was dominant and showed its highest abundance in the range 15-20 m. In the range 20-25 m, PN and CR showed their highest abundance, but NO was the dominant species. From 25 m and farther, only PN, NO and CR were present, being PN the dominant species. Some individuals of VT were located farther, particularly in 20-25 and 30-35 m.

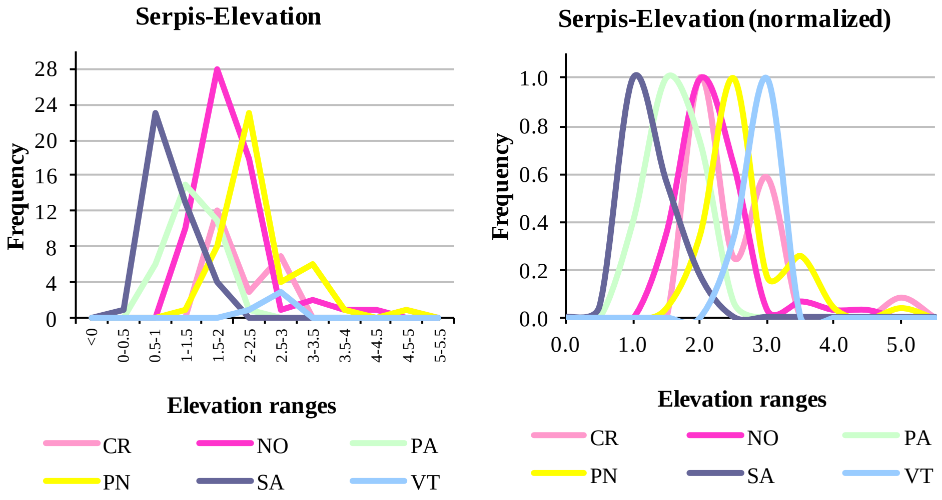


Figure 2.53. *Dominance curves of the riparian species respect to the elevation above thalweg at the Serpis-Lorcha study reach.*

Regarding elevation above thalweg (**Figure 2.53**), SA exhibited its highest abundance and dominance at the lowest elevations (band 0.5-1 m above thalweg). In the next band (1-1.5 m), PA was dominant and showed its maximum abundance, being accompanied by SA and NO. In the band 1.5-2 m above thalweg, NO was the dominant species and showed its highest abundance value, along with CR. Other species present at that range were PA and PN but with lower values. PN showed its highest abundance and was dominant at the range 2-2.5 m above thalweg. A big proportion of individuals of NO were present at that range as well. Finally, in the range 2.5-3 m, VT showed its highest abundance value, but due to its small sample size, other were the dominant species at that range, such as PN and CR.

2.5.2.5.4 Soil characteristics

Ten soil types were identified at Serpis-Lorcha study reach (**Figure 2.54**). Soils 6, 7, 9 and 10 had a quite similar coarse texture (gravel content around 60 %). Soils 3 and 8 were predominantly composed by sand (sand content 47 and 57 %, respectively) and soils 1, 2 and 4 by silt (silt content > 50 %). All of the soils had a content of clay lower than 10 %, except for soil 4 that got 16 %. In the soil type 5, two soil samples were collected due to important differences were detected between the surface and the bottom of the soil pit. An average of the values of each parameter for both samples was considered in the next analyses with plant species.

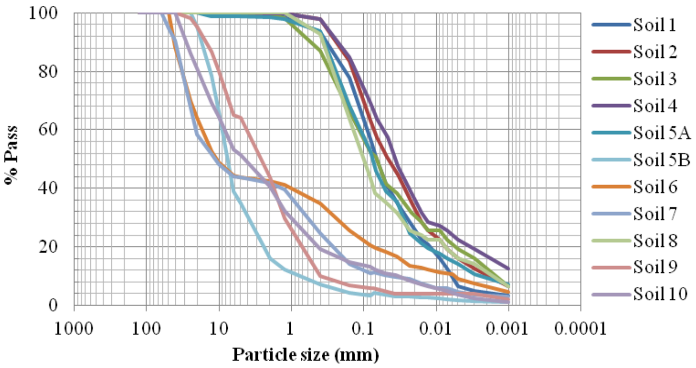


Figure 2.54. *Grain size distribution of the soil samples of the Serpis-Lorcha study reach.*

In relation to the organic matter and moisture content (**Figure 2.55**), a general coupled trend was identified for both parameters. Soil 5 presented the highest values for both parameters (3.6 % of organic matter and 36.7 % of moisture), while soil 9 presented the lowest (0.5 % of organic matter and 1.3 % of moisture). Both soils were located near the water's edge and at low elevations, but soil 9 was composed by a higher content of sand and gravel and lower content of silt and clay than soil 5. On the other hand, soil 6 exhibited a high percentage of organic matter but low moisture content (2.7 % of organic matter and 3.8 % of moisture), probably due to its high elevation and proximity to old forest stands.

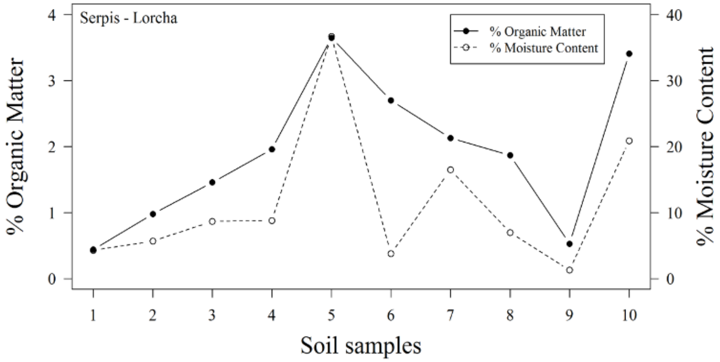


Figure 2.55. *Percentages of organic matter and moisture content in the ten soil samples analyzed in the Serpis-Lorcha study reach.*

All possible comparisons were carried out for the analyses of soil patterns. However, some tests did not performed well when all of the species were considered, due to the small sample size of some of them (PA = 15; CR = 15; VT = 4). For this reason, *tr* = 10 % and $\alpha = 0.05$ were considered as the most appropriate values to implement the tests.

A decreasing trend in the gravel content selected by the species was detected as we moved upwards in the elevation gradient (species in **Figure 2.56** and **Figure 2.57** appeared ordered according to the ranking defined by the Huber estimator for elevation above thalweg). The opposite, an increasing trend, was found for the other textures. In all cases, SA showed some of the lowest values, and NO and PN the highest values, except in the case of the gravel content. The K-W test showed significant differences (test value = 16.17; $p < 0.001$) among SA, NO and PN. The multiple comparisons showed two groups of homogeneous species: [SA] and [NO-PN]. SA presented 40 % of gravel as average in its locations while NO and PN presented values lower than 10 %. Considering all the species and 0.10 as significance level a new group could identified, that formed by [SA-PA]. Regarding the sand content, significant differences were found among species (K-W = 13.49; $p = 0.001$). The multiple comparisons showed two groups of homogeneous species: [NO] and [SA-PN]. NO exhibited a higher percentage of sand in comparison to SA and PN, but the values were not very different (40 respect to 30 %).

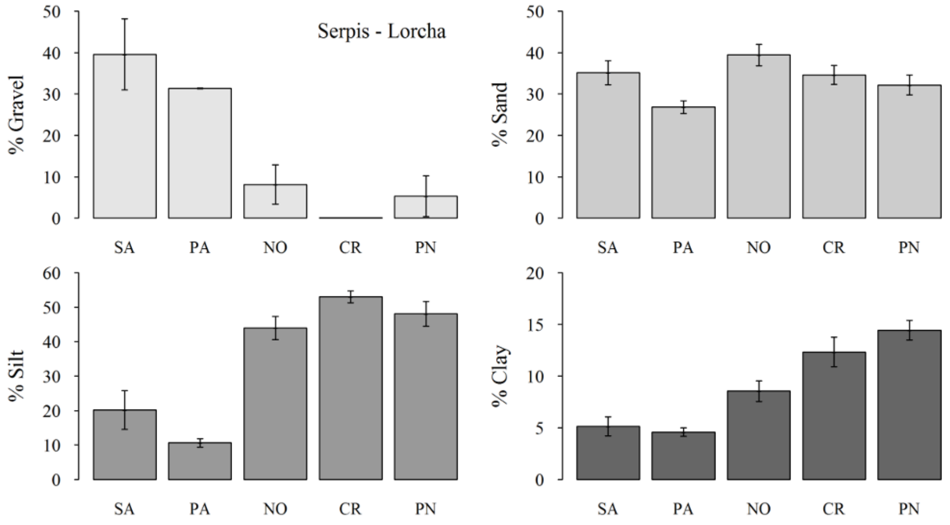


Figure 2.56. *Barplots with error bars for the percentage of gravel, sand, silt and clay for each species at the Serpis-Lorcha study reach. The height of the bars represents the mean values and the whiskers represent the confidence interval for the standard error. Species appear in ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.*

With respect to the silt content, significant differences ($FWe = 38.53$; $p < 0.001$) were detected as well. In this case, the homogeneous groups were the same that those showed in relation to the gravel content, i.e., [SA] and [NO-PN]. Similarly, considering all the species and 0.05 as significance level, two new groups could be identified, those formed by [SA-PA] and [CR-PN]. Using $tr = 20$ % and $\alpha = 0.10$, the species could be classified just into two groups [SA-PA] and [NO-CR-PN], having the first group a silt content average around 15 % and the second around 50 %. Significant differences were detected regarding clay, for SA, NO and PN (*FWe* = 108.09; $p = 0$). However, considering the five species, *tr* = 10 % and α = 0.05, two new groups could be defined: [SA-PA] and [CR-PN] with a 5 % of clay in average the first group and a 13 % the second group.

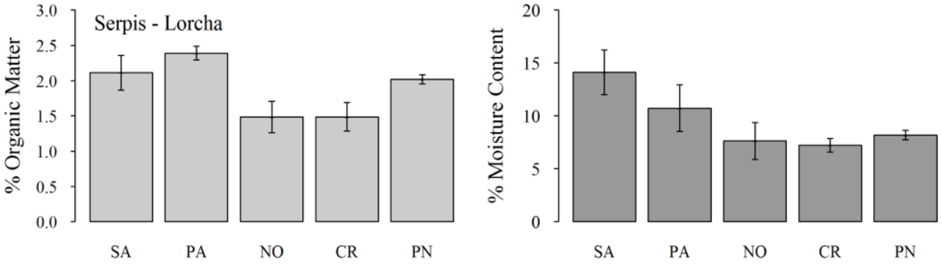


Figure 2.57. *Barplots with error bars for the percentage of organic matter and moisture content for each species at the Serpis-Lorcha study reach. The height of the bar represents the mean value and the whiskers represent the confidence interval for the standard error. Species appear in ascendant order according to the ranking defined by the Huber estimator for elevation above thalweg.*

In relation to the organic matter content (**Figure 2.57**), significant differences were found (K-W = 36.23; $p < 0.001$). Two homogeneous groups were obtained, those formed by [SA-PN] and [NO], with slightly higher values for the first than for the second group. Finally, regarding the moisture content, a decreasing trend was detected along the elevation gradient. The tests showed significant differences (*FWe* = 38.7; $p < 0.001$) among the three main species [SA], [NO] and [PN], being SA the species with higher preferences of moisture (mean 14 %), followed by PN and NO (mean approx. 8 %), but having NO a higher variability than PN. In general, PA performed similarly to SA, and CR to PN and NO, although these results should be considered with caution due to their sample size. Regarding VT, given that it was the species appearing farther from thalweg, the soils were similar to those showed by PN and CR. i.e., fine texture, high organic matter content and intermediate moisture.

2.5.2.5.5 Multivariate interpretation

The interaction between species and physical variables at the Serpis-Lorcha is illustrated in **Figure 2.58**; the first two axes explained 74.7 % of the total variance.

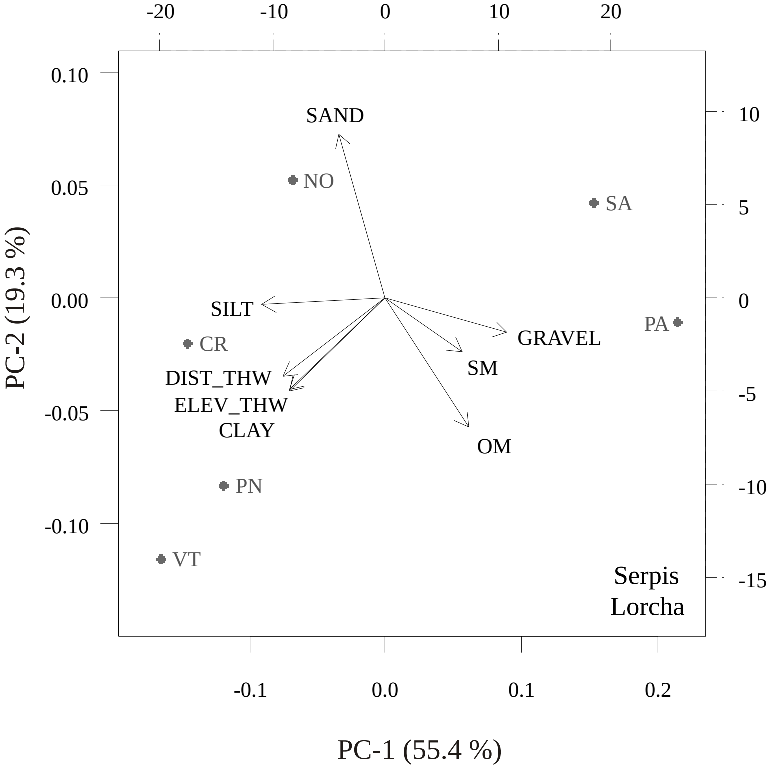


Figure 2.58. *PCA (principal components analysis) diagram for the Serpis-Lorcha study reach. Woody riparian species (dots in grey colour) are abbreviated as: NO, Nerium oleander L.; SA, Salix atrocinerea Brot.; CR, Crataegus monogyna Jacq.; PN, Populus nigra L.; PA, Populus alba L.; VT, Viburnum tinus L.*

The first axis (55.4 % of the variance) was positively related to GRAVEL (0.9) and negatively to SILT (-1.0), DIST_THW (-0.8), ELEV_THW (-0.7) and CLAY (-0.7). The second axis (19.3 % of the variance) was positively related to SAND (0.8).

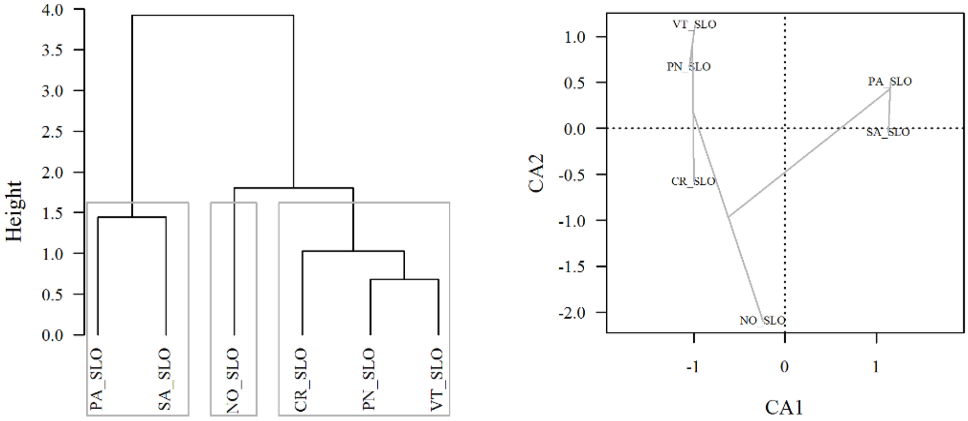


Figure 2.59. *Left plot, hierarchical cluster dendrogram (average clustering with Euclidean distance) based on the first three PCA scores for the woody riparian species recorded at the Serpis-Lorcha study reach. The vertical axis shows the level of fusion and is based on the dissimilarities between species. Right plot, clustering results overlaid onto an ordination diagram based on the proximity matrix. Cluster centroids are connected to each other with line segments similarly as in the original cluster dendrogram.*

The cluster analysis (**Figure 2.59**) explained 85.0 % of the variability. Although PA and SA were considered different in the multiple comparisons, the cluster and ordicluster grouped them. The PCA revealed that both species could composed a group located close to thalweg in distance and elevation and in soils with coarse substrate (high gravel content and low silt and clay content), and high organic matter and soil moisture. A second group could be defined by NO, located in intermediate positions with high sand content, low organic matter and high variability in soil moisture. A third group could be defined by PN, accompanied by CR and VT. It would be located farther from the water's edge, and in fine textured soils with intermediate levels of organic matter. Therefore, the riparian groups at the Serpis-Lorcha study reach could be defined as follows: [SA-PA], [NO], [PN-VT-CR].

2.6 RESULTS II

2.6.1 Comparison inter-sites

The overall richness of woody riparian species was higher in the unregulated sites than in the regulated ones. Cabriel-Rabo del Batán (CRA) presented the highest richness with ten species, followed by Mijares-Terde (MTE) with eight species. Both regulated sites in the Mijares River, Cirat (MCI) and Tormo (MTO), presented seven species and Serpis-Lorcha (SLO) presented only six species, the lowest value of the reaches analysed. Special attention deserves the ratio between tree and shrubs species. In this sense, the unregulated CRA and MTE exhibited an equitable ratio (the same number of tree species and shrub species: 5/5 and 4/4, respectively), whereas at the regulated reaches the shrubs species were always more abundant than the trees (1/6 at MCI, 1/6 at MTO and 2/4 at SLO).

The standard deviation of the length of the transects differed between sites. It was higher in the unregulated sites (CRA: 19; MTE: 14) than in the regulated sites (MCI: 11; MTO: 13; SLO: 8), suggesting a more heterogeneous shape in the former sites. In terms of cover, data suggested that CRA had the highest complexity (cover: 140 %), i.e., several layers or strata of vegetation were present. It was followed by MTO (97 %). The rest of the sites showed similar cover values (MTE: 78 %; MCI: 74 %; SLO: 72 %).

Apart from the richness, length of the transects and cover, where the sites showed to be clearly different, the multivariate analyses helped us to compared them according to their river morphology (distance and elevation ranges occupied by plants) and soil characteristics. In this sense, the classification strength test allowed the comparison of the variability of the study sites according to three different classifications: by status, by river and by sites (**Figure 2.60**).

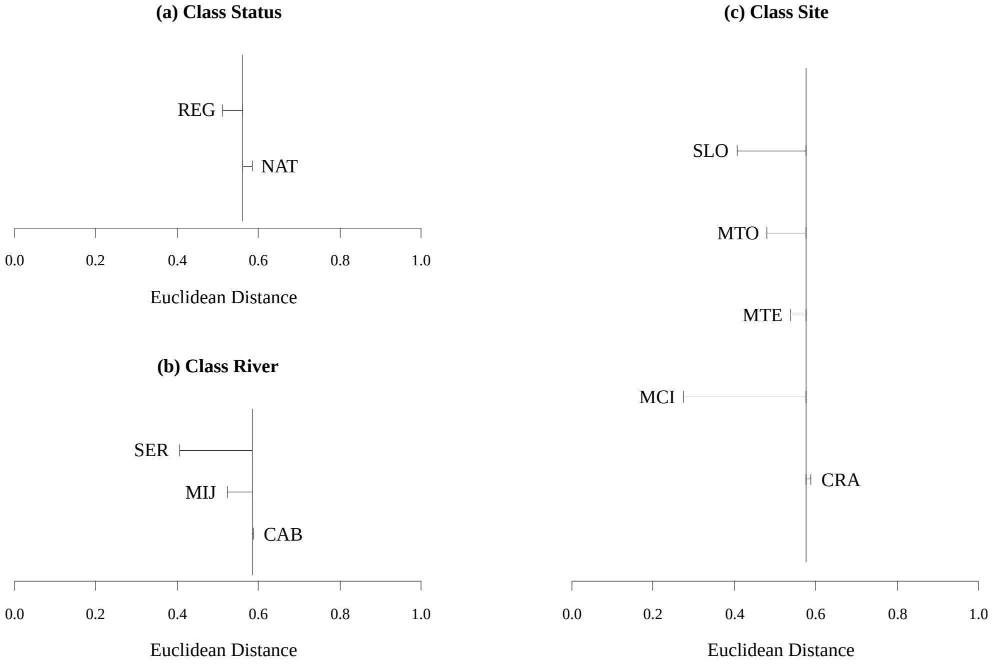


Figure 2.60. *Dendrograms obtained from the classfication strength test for the different classifications (a) class Status (NAT, natural; REG, regulated), (b) class River (CAB, Cabriel; MIJ, Mijares; SER, Serpis) and (c) class Site (CRA, Cabriel-Rabo del Batán; MCI, Mijares-Cirat; MTE, Mijares-Terde: MTO, Mijares-Tormo; SLO, Serpis-Lorcha). The mean inter-group dissimilarity is indicated at the foot of the vertical line (trunk); the difference between the inter-group dissimilarity and within-group mean dissimilarity (Wi, end of the branch) is represented by the length of the horizontal line (branches).*

The classifitcation by status (natural *vs.* regulated) was no statistically significant (p = 0.99). The classification strength was $\mathrm{CS} = -0.004\ (\overline{\mathrm{B}} = 0.562; \overline{\mathrm{W}} = 0.566)$, therefore, both groups were homogeneous in relation to the whole dataset (i.e. almost equal dissimilarity within and between classes was found), suggesting no class structure. On the contrary, the classification by river was statistically significant (p<0.01) but similarly, the classification strength showed a low value $\mathrm{CS} = 0.046\ (\overline{\mathrm{B}} = 0.585; \overline{\mathrm{W}} = 0.539)$ revealing no clear class structure. Among the three rivers, the Serpis River showed the most homogenous data and the

Cabriel River the most heterogenous. Finally, the classification by study sites was statistically significant (*p*<0.01) and had a classification strength of $\text{CS} = 0.050\ (\overline{\text{B}} = 0.576;\ \overline{\text{W}} = 0.526)$. The dendrogram (**Figure 2.60 c**) showed the variability among sites. Those regulated were shown as more compact and homogenous (longer branches to the left) than those free-flowing. In general, all the sites showed lower values of $\overline{\text{W}}\text{i}$ than $\overline{\text{B}}$. In order, MCI was the most homogeneous, followed by SLO, MTO and finally, MTE. This meant that the variability within each site was lower than the mean variability between sites, except for CRA, the most heterogeneous site, with larger variability than the mean variability of the rest of the sites.

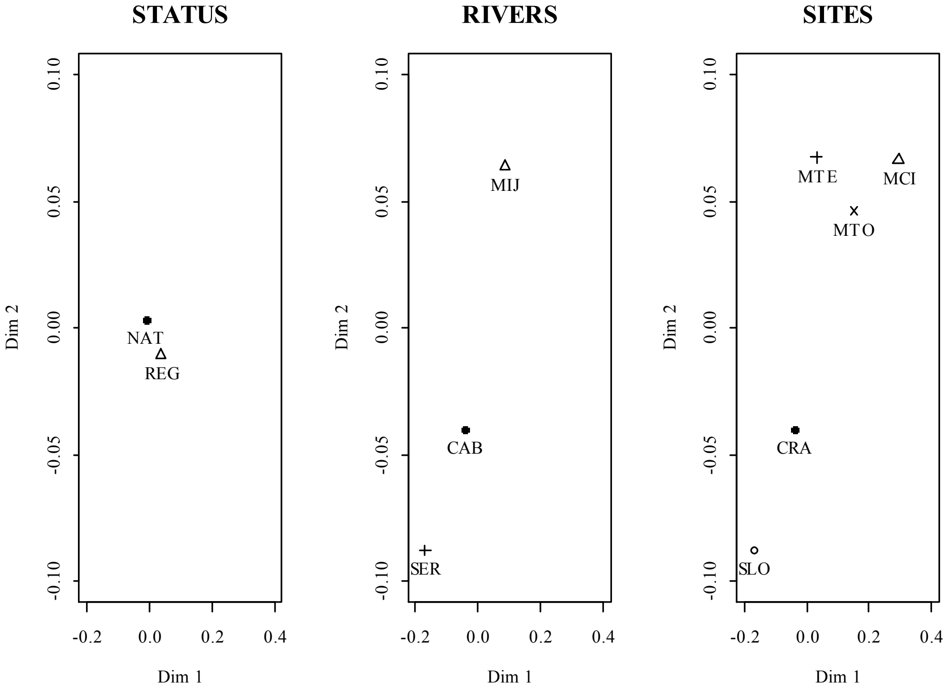


Figure 2.61. *Metric multidimensional scaling (MDS) of the mean distances for the different classifications (a) class Status (NAT, natural; REG, regulated), (b) class River (CAB, Cabriel; MIJ, Mijares; SER, Serpis) and (c) class Site (CRA, Cabriel-Rabo del*

Batán; MCI, Mijares-Cirat; MTE, Mijares-Terde: MTO, Mijares-Tormo; SLO, Serpis-Lorcha).

The metric multidimensional scaling (MDS) confirmed the results obtained from the classification strength (**Figure 2.61**) but it offered a visualization in a two-dimensional space. The three sites from the Mijares River appeared closer on the top right, revealing their similar characteristics in spite of being MTE free-flowing and MCI and MTO regulated. SLO appeared in the opposite location (bottom left), and CRA in a intermediate position.

2.6.2 Distribution patterns and soil characteristics of coincident species

Once the transverse structure of each site was studied here, the distribution patterns of the coincident species among sites were analysed. In **Table 2.3** and **Figure 2.62** can be seen the coincident species. The comparisons were carried out when a certain species was present at least in two sites and the sample size for each was larger than 15. In consequence, ten was the number of coincident species analysed. Eight of them appeared just in two sites (SL, SA, SP, PA, NO, TA, CM and CR), one in four sites (SE) and one in five sites (PN). **Figure 2.62** shows a summary of the comparisons between coincident species in terms of distribution patterns and soil characteristics.

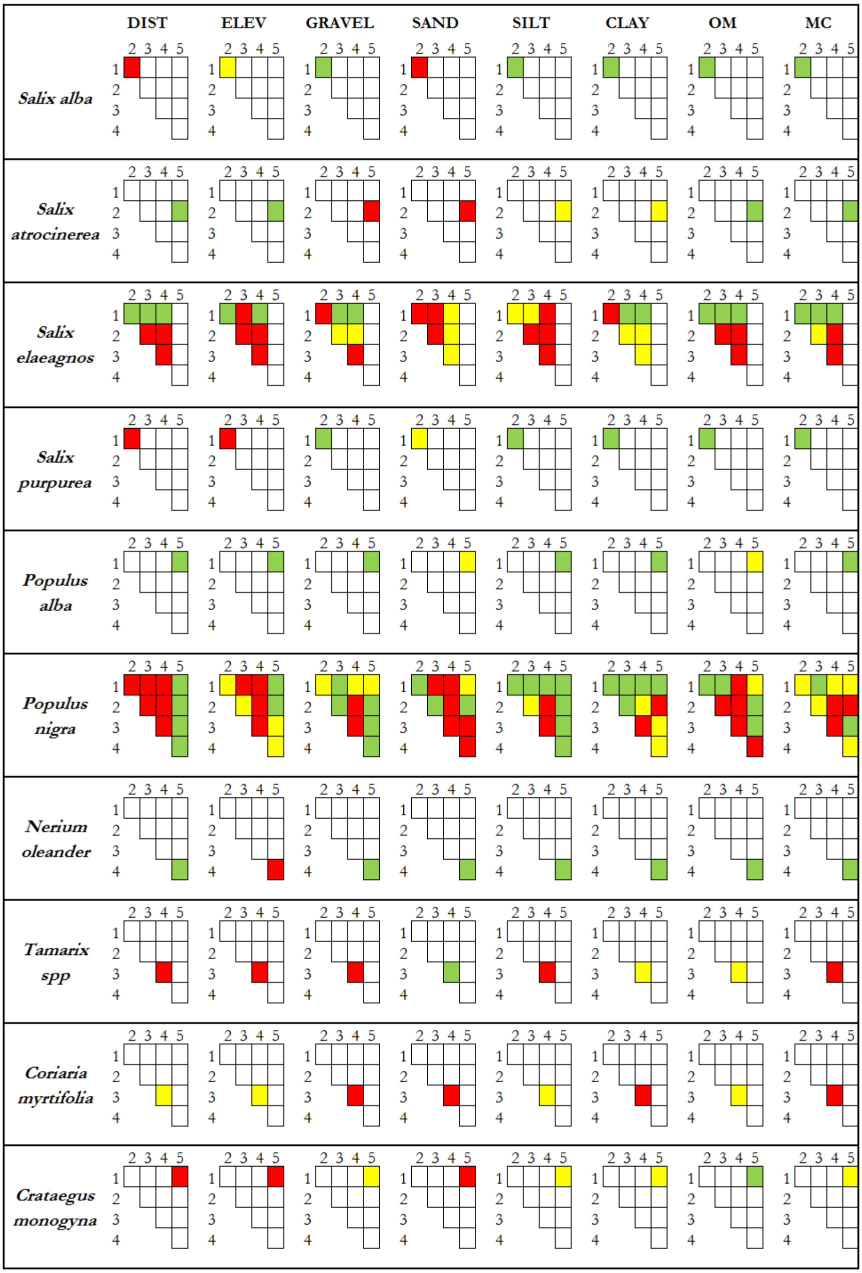


Figure 2.62. *Summary of the coincident species among sites (1: Cabriel-Rabo del Batán; 2: Mijares-Terde; 3: Mijares-Cirat; 4: Mijares-Tormo; 5: Serpis-Lorcha). Colour codes:*

red-no significant differences; green-significant differences; yellow-significant differences depending on the trimming percentage and significance level assigned. Variable codes: DIST-distance to thalweg; ELEV-elevation above thalweg; GRAVEL-gravel content; SAND-sand content: SILT-silt content; CLAY-clay content; OM-organic matter content; MC-moisture content.

Salix alba (SL) was present in CRA and MTE (**Figure 2.62** and **Figure 2.63**). This species was positioned in similar locations in both unregulated sites, hovering around 8 m distance to thalweg and 1.2 m above thalweg. Significant differences were detected in the soils (texture, organic matter and moisture content), except for the sand content, where no differences were found (average value: 36 %).

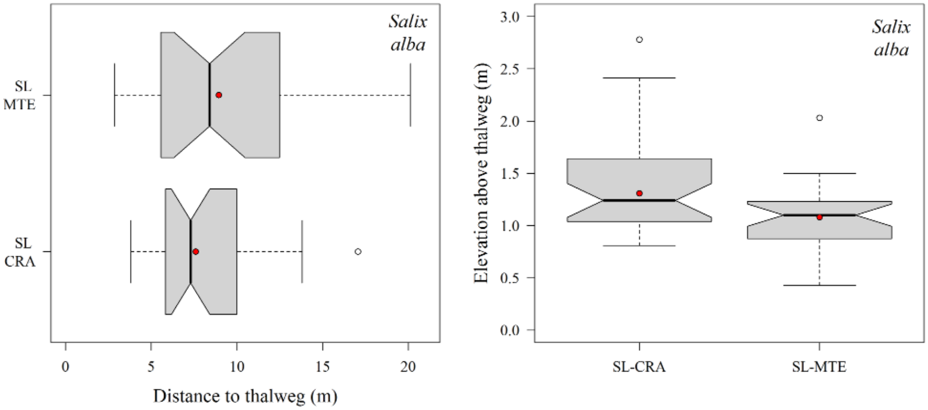


***Figure 2.63.** Boxplots of the distribution (left plot - distance to thalweg; right plot-elevation above thalweg) of the specimens of Salix alba (SL) sampled at the Cabriel-Rabo del Batán (CRA) and Mijares-Terde (MTE) study reaches. Red dots represent the Huber estimator.*

Salix atrocinerea (SA) was present in MTE and SLO (**Figure 2.62** and **Figure 2.64**). Significant differences were found in the location of the specimens of this species in both sites, unregulated and regulated. In terms of distance, SA appeared closer to thalweg in MTE than in SLO (6.8 and 12.4 m according to their Huber estimators, respectively), but on the contrary, it appeared closer to thalweg in SLO in terms of elevation (1 m respect to 1.5 m in MTE). No significant differences were detected in relation to gravel and sand. However, they showed differences in terms of organic matter and moisture content (higher values in SLO than in MTE).

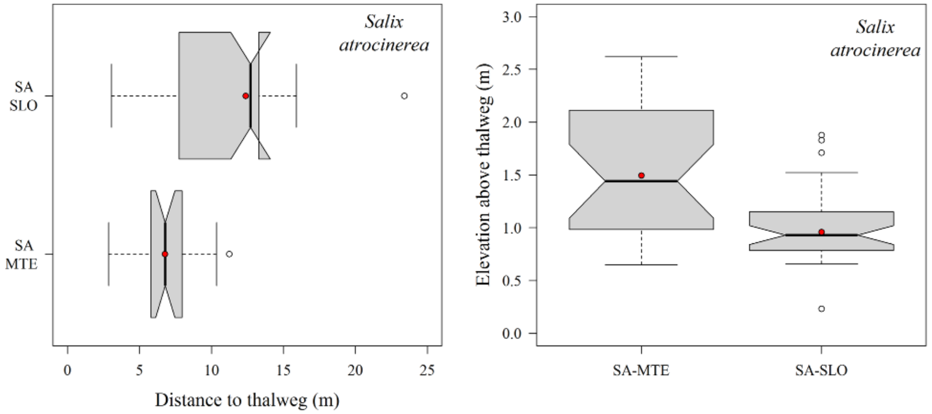


Figure 2.64. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the specimens of Salix atrocinerea (SA) sampled at the Mijares-Terde (MTE) and Serpis-Lorcha (SLO) study reaches. Red dots represent the Huber estimator.*

Salix eleagnos (SE) was present in CRA, MTE, MCI and MTO (**Figure 2.62** and **Figure 2.65**). Regarding distance to thalweg, no significant differences were found in the three sites of the Mijares River. The Huber estimator was 6.5 m in MTO, 7.7 in MTE and 9.1 in MCI. However, it was 22.4 m in the case of the CRA, revealing significant differences in the comparison. Similar results were obtained in relation to the elevation above thalweg, but in that case, no significant differences were found between CRA and MCI. The Huber estimator gave values between 1 and 2 m above thalweg. The lowest values appeared in MTO and MTE (1 and 1.3, respectively) and the highest values in MCI and CRA (1.7 and 1.9 m, respectively). Regarding soils, no significant differences were found between CRA and MTE in gravel, sand and clay content, but they differed in organic matter and moisture content. CRA differed with MTO and MCI in sand, clay, organic matter and moisture content but not in sand and silt. No significant differences appeared between MTE and MTO and MCI in terms of silt, organic matter and moisture content. Differences in the other soil variables depended on the test parameters.

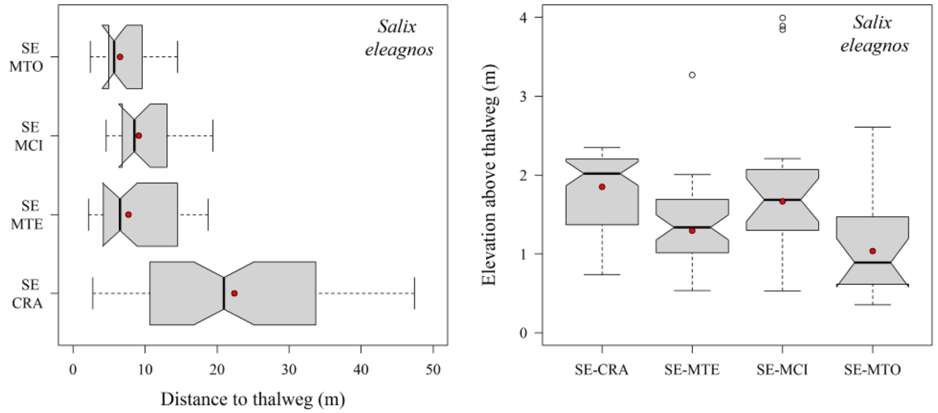


Figure 2.65. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the specimens of Salix eleagnos (SE) sampled at the Cabriel-Rabo del Batán (CRA), Mijares-Terde (MTE), Mijares-Cirat (MCI) and Mijares-Tormo (MTO) study reaches. Red dots represent the Huber estimator.*

Salix purpurea (SP) was present in CRA and MTE (**Figure 2.62** and **Figure 2.66**). No significant differences were found in terms of distance and elevation above thalweg in both unregulated sites. The Huber estimator gave values of 8.5 m and 9.1 m respectively, in distance to thalweg. Similarly, it gave values of 1.1 and 1.2 m, respectively, in terms of elevation. Nevertheless, significant differences were found between both sites for all the soil parameters. The specimens at MTE were associated with higher gravel and sand content, and lower silt, clay, organic matter and moisture content than in CRA.

Populus alba (PA) was present in CRA and SLO (**Figure 2.62** and **Figure 2.67**). Significant differences were found between all of the variables for both sites, although in terms of sand and organic matter content the differences depended on the trimming percentage and significance level applied. The specimens of PA at SLO were located closer to thalweg, both in distance and elevation.

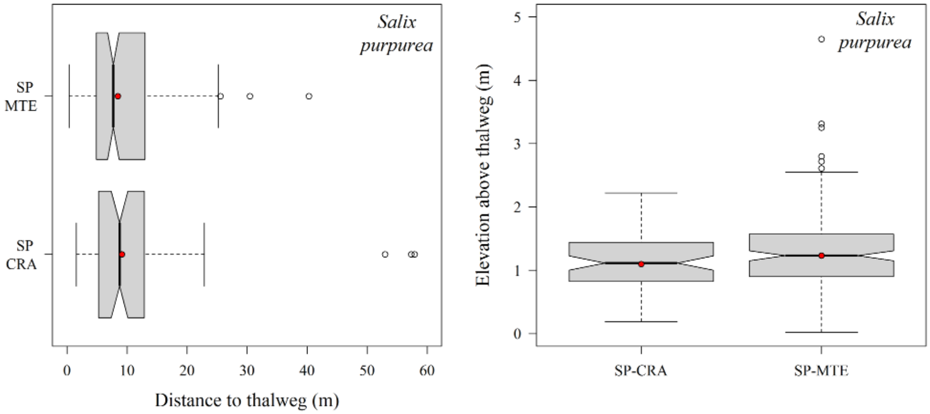


Figure 2.66. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the specimens of Salix purpurea (SP) sampled at the Cabriel-Rabo del Batán (CRA) and Mijares-Terde (MTE) study reaches. Red dots represent the Huber estimator.*

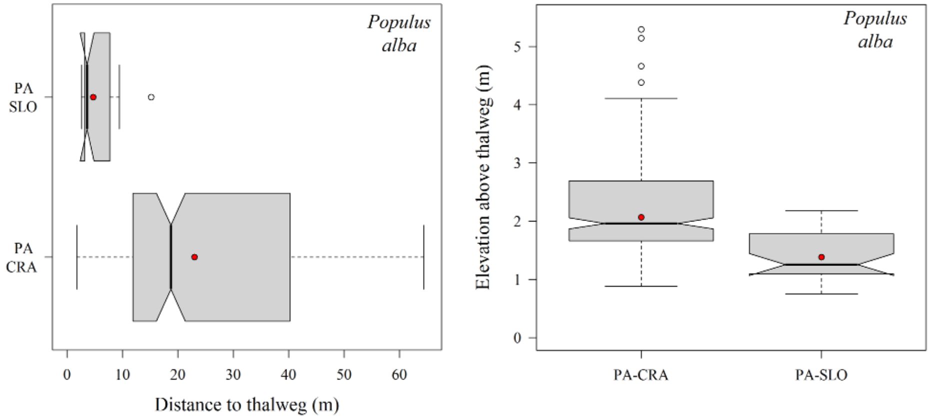


Figure 2.67. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the specimens of Populus alba (PA) sampled at the Cabriel-Rabo*

del Batán (CRA) and Serpis-Lorcha (SLO) study reaches. Red dots represent the Huber estimator.

Populus nigra (PN) was present in all of the study sites (**Figure 2.62** and **Figure 2.68**). No significant differences were found in terms of distance to thalweg, except for SLO with the rest of them. Regarding elevation, only clear differences appeared between CRA and MTE respect to SLO (i.e. unregulated *vs.* regulated sites). No differences appeared between CRA-MCI, CRA-MTO, MTE-MTO and MCI-MTO. In the rest of combination of sites, the differences depended on the test parameters. Considering all of the sites (except SLO), PN was located in a range 1.4-1.9 m above thalweg and 9.3-11.8 m to thalweg. Regarding soil characteristics, CRA and SLO were established as the most different sites, and MTE-MTO and MCI-MTO as the most similar ones (for all the soil parameters). No differences appeared in sand content among the three regulated sites, although significant differences were found in gravel and silt.

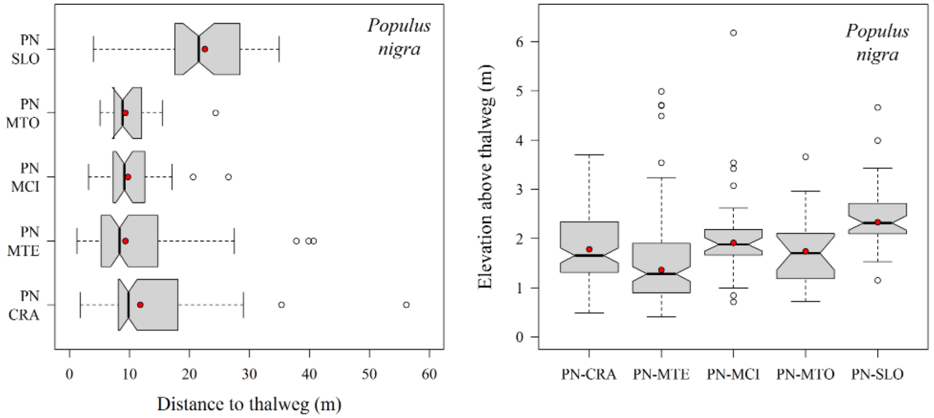


Figure 2.68. *Boxplots of the distribution (left plot - distance to thalweg; right plot-elevation above thalweg) of the specimens of Populus nigra (PN) sampled at the Cabriel-Rabo del Batán (CRA), Mijares-Terde (MTE), Mijares-Cirat (MCI), Mijares-Tormo (MTO) and Serpis-Lorcha (SLO) study reaches. Red dots represent the Huber estimator.*

Nerium oleander (NO) was present in MTO and SLO (**Figure 2.62** and **Figure 2.69**). Significant differences were found for all of the variables between both regulated sites, except for the elevation above thalweg, where no significant differences were detected (Huber estimator around 1.85 m). In relation to distance, the specimens of NO were located closer to thalweg in MTO than in SLO (9.0 m respect to 17.7 m).

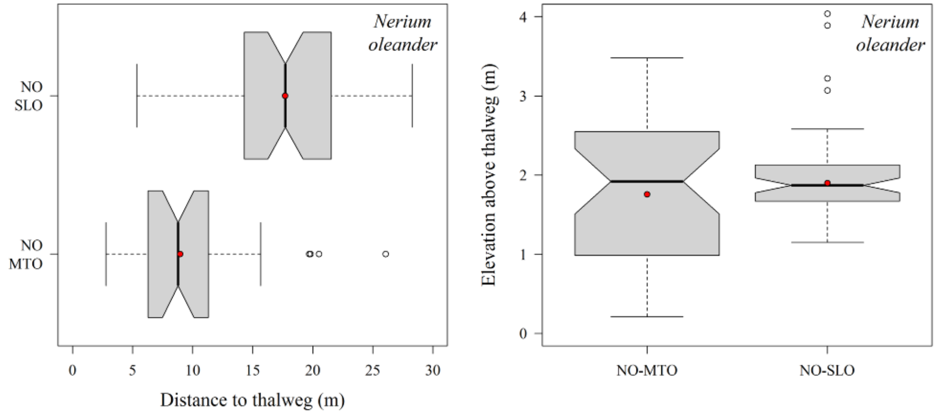


Figure 2.69. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the specimens of Nerium oleander (NO) sampled at the Mijares-Tormo (MTO) and Serpis-Lorcha (SLO) study reaches. Red dots represent the Huber estimator.*

Tamarix spp. (TA) was present in MCI and MTO (**Figure 2.62** and **Figure 2.70**). No significant differences were found in any of the variables, except for the sand, which was higher in MCI, clay content and organic matter content. The mean clay content was higher in MCI but the organic matter content was higher in MTO. The specimens of TA in MTO were closer to thalweg (in distance and elevation) than those in MCI.

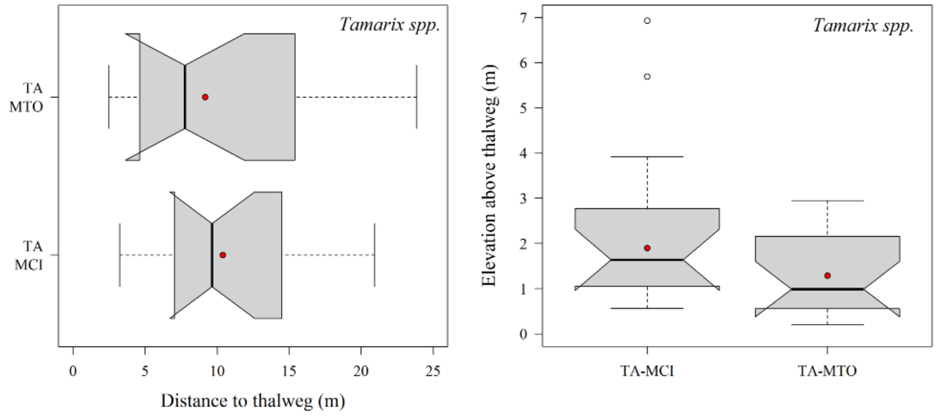


Figure 2.70. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the specimens of Tamarix spp. (TA) sampled at the Mijares-Cirat (MCI) and Mijares-Tormo (MTO) study reaches. Red dots represent the Huber estimator.*

Coriaria myrtifolia (CM) was present in MCI and MTO (**Figure 2.62** and **Figure 2.71**). Similarly to TA, no significant differences took place between both regulated sites for most of the variables. According to the test parameters, differences could be found in DIST, ELEV, SILT and OM. The specimens of CM in MTO were closer to thalweg (in distance and elevation).

Crataegus monogyna (CR) was present in CRA and SLO (**Figure 2.62** and **Figure 2.72**). No significant differences appeared in distance, elevation and sand content. According to the Huber estimator, all the specimens of this species were around 21 m to thalweg and 2.1 m above thalweg. Only clear differences were found in terms of organic matter. The differences in the rest of soil variables depended on the test parameters.

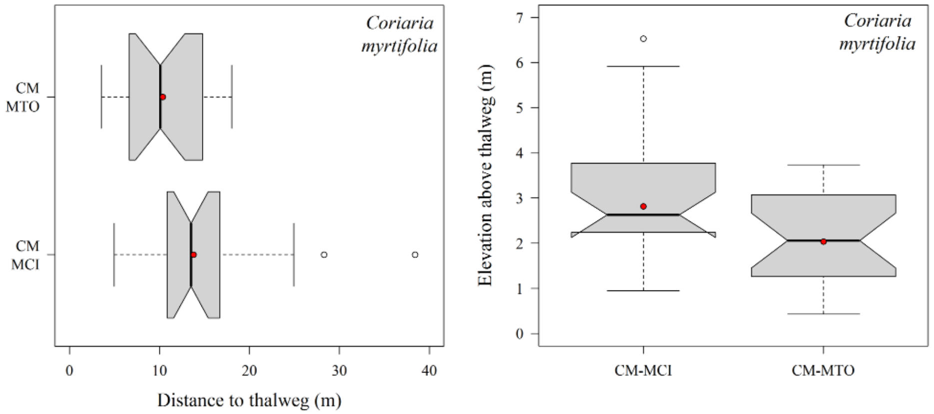


Figure 2.71. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the specimens of Coriaria myrtifolia (CM) sampled at the Mijares-Cirat (MCI) and Mijares-Tormo (MTO) study reaches. Red dots represent the Huber estimator.*

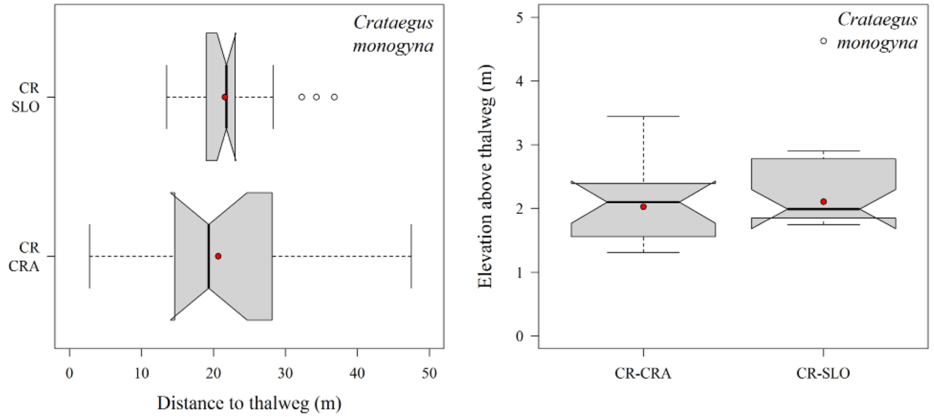


Figure 2.72. *Boxplots of the distribution (left plot - distance to thalweg; right plot- elevation above thalweg) of the specimens of Crataegus monogyna (CR) sampled at the Cabriel-Rabo del Batán (CRA) and Serpis-Lorcha (SLO) study reaches. Red dots represent the Huber estimator.*

2.7 DISCUSSION

Recording the position (in reference to the river thalweg) of the main woody riparian species along cross-sectional transects in river reaches, as well as their soil characteristics, allowed us the assessment of species groups with similar spatial patterns. Additionally, we compared the behavior of ten different woody riparian species between regulated and unregulated reaches.

2.7.1 Riparian vegetation composition and zonation

Five study reaches were surveyed in the Júcar River Basin District (East Spain) to implement this study. All of them had a good riparian quality status but different level of regulation of their flow regime. In total, 1852 specimens of 18 species were recorded within the five sites. The small sample size presented by some species was more related to phytogeographic reasons than human-induced alterations, i.e., their scarcity might be more a consequence of being in the outer range of their optimal distribution.

The unregulated sites (CRA and MTE) had a more heterogeneous shape of the riparian habitats, showed higher richness of species and a more equitable balance between tree and shrub species than the three regulated sites (MCI, MTO and SLO). According to the hypothesis of intermediate disturbance, those places with disturbances of intermediate intensity host a higher species richness because of a mix of species with different requirements (Lite *et al.*, 2005). Therefore, a lower richness could be due to a more stable flow regime in the regulated sites, which could have led to a decrease in the fluvial heterogeneity and level of disturbances, and hence, a reduction of the fluvial biodiversity, as other studies have pointed out, for example Naiman *et al.* (2006).

Both unregulated sites were located in the headwaters of the Cabriel and Mijares rivers and belong to the river ecotype 12 '*rivers in calcareous Mediterranean mountain*'; however, the regulated sites were located in the middle reaches of the Mijares and Serpis rivers and belong to the ecotype 9 '*mineralised rivers in middle* *and low Mediterranean mountain*' (CHJ, 2009b). Thus, besides the regulation effects, climatic and geomorphological conditions also played their role and could have promoted a more shrubby than arboreal configuration of the riparian corridor of the regulated sites.

The comparison between abundance and cover values was established as an easy way to determine the complexity and structure of the riparian corridor within each site. CRA was the site with the highest cover values, followed by MTO. We think that the higher cover of these two sites revealed their higher complexity for two different reasons. In the case of the CRA, the vegetation was developed under natural processes and a variety of successional stages were found during the surveys; however, in the MTO the vegetation was in an advanced status (of age classes) because of the lack of disturbances after the hydropower dam closure upstream and a severe flow regulation (Garófano-Gómez *et al.*, *in press*). This fact was revealed because a high proportion of terrestrial and late successional species within the riparian corridor was detected. For instance, *Viburnum tinus* (VT) exhibited more abundance of stems than cover, which suggested us that the vegetation in MTO was becoming older and more terrestrial. Besides, the specimens of proper riparian pioneer species such as *Salix atrocinerea* (SA) were in a very mature stage.

The other regulated site in the Mijares River, MCI, was very similar to MTO in terms of vegetation composition, richness, transects' length and position of the species. However, MCI had a smaller total cover value in comparison with the rest of sites. This could be due to the influence of agriculture and because in this site there was an important proportion of non-woody species, and therefore, not target in this study, such as *Phragmites australis*, *Arundo donax, Typha latifolia, Doricnium rectum*, etc. In both sites the presence of *Rubus ulmifolius* was relevant as well. The climbing configuration of this plant did not allow its inclusion in this geo-referenced study of vegetation.

2.7.2 Transverse variation across the floodplain: definition of groups

In CRA, four groups were found in terms of distance and elevation, but clearer differences appeared in elevation and the groups were better defined and mimicked the gradient in the soil conditions. In order of elevation, these groups were [SP, SL], [SL, FA, PN], [PN, PA, SE] and [PC]. The terrestrial PC was established as a completely different group although that was not so clear during the field surveys and in fact, in terms of distance it appeared mixed with PA and SE, revealing a transitional change from riparian to terrestrial conditions in this site. SL and PN were the species that intermediated the change from one group to the other. The soil trends in CRA differed from the soil trends showed by the other sites. The sand content was very high in the entire site. The gravel content increased from the water's edge to the upland zone dominated by PC (except in the areas where specimens of SP were located, which contained higher values). On the contrary, the silt and clay content decreased in the elevation gradient.

In the case of the MTE, it was very clear the separation between proper riparian and terrestrial species (it took place around 15 m from thalweg and 2.5 m above thalweg), so according to the morphological variables, the groups obtained were [JU, QC] and [SL, SP, SE, PN, SA]. The riparian group was composed only by species of Salicaceae family. They were found on a wide variety of soils. These species can easily withstand water-level fluctuations and usually remain on river banks permanently, behaving like pioneers due to their facility for vegetative propagation and their ability to take root again after periodic floods (Aránzazu-Prada and Arizpe, 2008). Between all the willows, SA showed a different behavior in terms of location and soil preferences (this will be explained later on). Both morphological variables produced different rankings, mainly due to the high complexity (several channels) and natural dynamism of this site. Nevertheless, the elevation (despite not showing differences among riparian species) indicated a gradual transition of species in the riparian zone. Both groups showed differences in the soil texture. The riparian group preferred higher gravel content as well as lower silt and clay content than the terrestrial group. These results are in accordance with the distance to the main channel and the development of the soil in farther locations.

In MCI, no clear groups could be defined statistically, although differences took place between the species located in the extremes of the transverse gradient. In general, three groups could be defined: first group composed by SP, SA and SE (closer to thalweg); second by TA and PN (in intermediate positions); and third by CM (at higher and farther positions). General trends appeared in the variability of soils according the species' positions along the transverse gradient but without statistically significant differences. This could happen in sites with low soil variability or absence of a clear species gradient.

In MTO, no differences appeared among species in terms of distance to thalweg. This could have been caused by the severe reduction of fluvial disturbances that would have allowed the colonization of the entire transverse gradient. In relation to the elevation, slight differences were detected between the species located most far apart in the floodplain, i.e., SE close to the water's edge and CM and VT with preference for higher elevations. However, this was the most regulated site and no groups could be defined, owe to the lack of differences among species. The two rankings depicted by both morphological variables were very similar and all the species showed their highest abundance values in the same range (5-10 m to thalweg). Similarly, in relation to soils, no groups were statistically significant, but differences appeared in the species located in the extremes of the elevation gradient (SE and TA respect to CM and VT).

In broad terms, two groups of species could be identified at the Serpis River. The first group closer to thalweg (in distance and elevation) was formed by SA and PA, while the second group (farther) was composed by NO-CR-PN. The same groups were identified in terms of soils. SA-PA was found in soils with higher content of gravel, organic matter and moisture. The opposite was found for NO-CR-PN. However, the statistical analysis separated SA and PA as two different groups in distance and elevation. This could be explained for the different profile of the Serpis River's banks. PA was located always in the right bank, which was at a higher elevation than the left bank, where most of the SA individuals were located.

2.7.3 Behavior of woody riparian species in regulated and unregulated sites

Although some exceptions occurred, no significant differences were detected between the specimens of a certain species in sites of the same kind, regulated or unregulated. Accordingly, they performed differently when the comparison involved sites with different flow regime.

Salix alba and *Salix purpurea* appeared only in the unregulated sites CRA and MTE because that was the outer range of their phytogeographic distribution (Aránzazu-Prada and Arizpe, 2008). No differences were found in the position occupied by these species in both sites, but differences occurred in terms of soil requirements, which may be determined at a more local scale.

Significant differences were found in the location of the specimens of *Salix atrocinerea* (SA) in MTE and SLO (unregulated and regulated, respectively). SA appeared closer to thalweg in SLO in terms of elevation. This fact may be due to the lack of disturbances and flow regulation. However, another possible reason would be the ecological function of this species in the succession scheme of both rivers. In the SLO, the potential vegetation close to the water's edge is 'sauceda negra', whose main integrant is SA, while in MTE, SA is a pioneer species living in the understory (it grows in partial shade and under full sunlight) and is able to co-dominate in the early successional woodland after other pioneer species (such as SP and SE) start to decline (Francés *et al.*, 2011). This fact also could explain the higher positions of SA in MTE respect to SLO and would explain the differences in soils in both sites (with higher organic matter and moisture content in SLO than in MTE). Similarly, *Populus alba* (PA) occupied closer positions to thalweg in SLO than in CRA, but in both cases the specimens occupied soils with high sand content.

Salix eleagnos (SE) showed different behaviour in CRA in comparison with the rest of the sites. This could be explained because the specimens of SE in CRA were located in secondary channels. It is likely that considering a different reference level as thalweg, the differences in distance and elevation would be less remarkable in comparison with those shown in the other sites. SE occupied the closest locations to thalweg in MTO, the most regulated site. Therefore, the lower location of the species in regulated sites is coherent with the general pattern of other species.

No clear conclusions could be drawn for *Populus nigra* (PN), besides it was the species with the highest uncertain origin of all the species considered. SLO was different from the rest of sites. The largest differences took place respect to the unregulated sites CRA and MTE.

Nerium oleander (NO) was only present in the sites with higher Mediterranean influence, this is MTO and SLO. The pattern was coincident in both rivers in terms of elevation. However, there were no coincidences in the other variables. In MTO, the oleander specimens were located slightly closer to thalweg.

No differences existed in the positional patterns of the specimens of *Tamarix* spp. (TA) in MCI and MTO. In general, they were slightly closer to thalweg in MTO. This could be caused by the higher regulation of MTO, which also could have an effect in the lower sand content (no income of new sediment, which is retained in the dam) and higher organic matter (no removal of vegetation).

Coriaria myrtifolia (CM) is restricted to coastal Mediterranean streams; for that reason, it was not present in the unregulated sites (out from its distribution range). This species requires moderately moist soils (Aránzazu-Prada and Arizpe, 2008) and certainly, it was located in the places with the highest moisture content at MCI and MTO. It occupied the same locations in both sites, but the specimens in MTO were slightly closer to thalweg (in distance and elevation) than those in MCI.

Crataegus monogyna (CR) is one of the riparian species with broader ecological range and greater taxonomic complexity (Aránzazu-Prada and Arizpe, 2008), what could be the reason why it did not show different behaviour in the unregulated CRA and regulated SLO study reaches. Only clear differences were found in terms of the organic matter preferences between the specimens in both sites.

2.7.4 Importance and uncertainty of the variables in the definition of groups

Although comparative analysis of the observed and predicted ground surface level was carried out in less than one percent of the total sample size, we could accept as valid the assumption of no differences between both points. In some cases, the predicted surface could be displaced respect to the observed in the field, for example in trees with a highly heterogeneous crown or because of the presence of physical barriers, such as bedrock outcrops. Nevertheless, this displacement would take place in a small proportion of cases over the entire database with no consequences in the results where a considerable high sample size is employed. Therefore, the use of the central point of the vertical projection of any plant was considered as a reasonably valid simplification to implement this study.

The two morphological variables studied, i.e., distance and elevation to/above thalweg, were considered as an easy way to measure indirectly other factors such as tolerance to inundation (Harris, 1986) and anoxia or capability to resist the drag forces caused by floods. Both variables led us to compare the species with a 'static' point of view based on the current morphology. In this way, the surveys showed the result of many hydrological cycles and repeated processes of vegetation succession and retrogression. According to Lite *et al.* (2005), both variables are negatively correlated with the inundation frequency. Hence, if a certain species appears located closer to thalweg than others, we could assume that the former has higher tolerance to inundation or it is better adapted to resist more frequent and longer periods of inundation than the later.

Between both variables, elevation above thalweg was considered to work better in distinguishing groups; accordingly, in previous studies the elevation has showed a stronger correlation than distance with inundation frequency (Lyon and Sagers, 1998). In addition, Lite *et al.*, (2005) observed that the elevation above thalweg showed a negatively relation with water table depth, which is not so patent in the case of the distance above thalweg. Given that elevation is less related to changes in morphology than distance, the conclusions from this variable are more potentially transferable between rivers. However, we assume an approximately homogeneous profile of the soil in the floodplain (a critical factor for the elevation of water table and capillary fringe), which can be unrealistic in some river reaches. In order to illustrate this issue, we include the figure by Meier (2008).

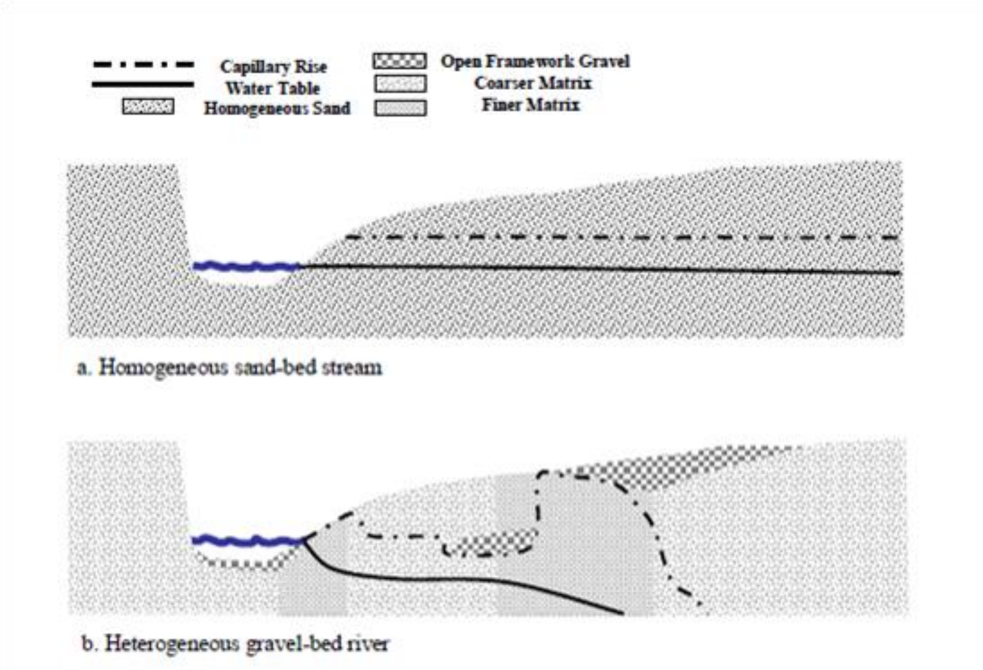


Figure 2.73. *Cartoon depicting the different behaviour of the alluvial water table and associated capillary fringe in the case of (a) sand-bed streams and (b) gravel-bed rivers. Please*

note that both depictions, but mostly (b), are gross oversimplifications as compared to the natural heterogeneity found in fluvial sedimentary deposits. Source: Meier (2008).

Moreover, according to our results, elevation above thalweg was a most robust measure than distance; the ordination produced by the median and the Huber estimator was more similar across sites in terms of elevation than in terms of distance. Apart from this, distance and elevation performed similarly when the channel was single, but when it was more complex the elevation still continued performing well. In this study, the natural (unregulated) sites had higher complexity than the regulated sites, in terms of morphology and species richness. This made more difficult to distinguish groups of species in them. However, the groups were clearer in terms of elevation than in distance which gave more noise where there was not a single and identifiable channel. Furthermore, the ordination of species produced by the elevation was more gradual and this helped to discriminate better the pattern of each species.

According to Lite *et al.* (2005), water availability may be a stronger limiting factor than disturbance along semi-arid region rivers. Apart from water availability, other variables that could determine the lateral vegetation pattern are related to the soil type, canopy (dense canopy influences the litter content and reduce light levels), nutrients availability... Depending on the soil properties, the communities are composed of plants tolerating episodic to permanent inundations. Plants tolerating inundation are bound to soils with low permeability. Well-permeable soils are the habitat of plants tolerating the often rapidly changing extremes of flooding and dryness. Although important differences occurred between the soil characteristics of the study reaches, some clear trends could be identified.

Regarding the organic matter content, no significant differences appeared between species in MTO and MCI sites. These could be also related to the small number of soil samples taken in those sites. However, a decreasing trend was observed in organic matter content in all the sites from the water's edge to the upland fringe. This could be explained because the valley is like a canyon in these reaches, and there is low organic matter content in the slopes. The riparian zone has a greater income coming from the trees than from the surrounding areas. The slopes are very rocky and the typical Mediterranean vegetation (*Pinus* and *Quercus*) do not produce so organic matter as the riparian species do, which are deciduous species. This fact was particularly patent in the Cabriel River, where the important canopy of this site could have magnified this phenomenon.

In some cases, the species located in a second line in the floodplain (e.g., SL and PN) experienced less moisture content than those located in the first line. However, the standard deviation was high in some cases, denoting variety of conditions across the floodplain and between the specimens of a particular species. According to Bagstad *et al.* (2006), the differences in the soil parameters may be more patent between different size/age class than between species.

Nonetheless, the position revealed for each species in the study reaches and the final patterns of the species should be interpreted with caution because all the studies present some kind of uncertainties. In our case, the most remarkable uncertainties can be defined as follow:

(i) the channel morphology, which can determine the position of the thalweg. In the case of a single channel, both distance and elevation can performed similarly, but in the case of a more complex channel, elevation could perform better than distance to thalweg as it has been explained before. The distance is more influenced by the position of the thalweg and the specific profile of the banks than by the elevation. If the cross-section is regular (case of a rapid, riffle or glide, habitat units in the main channel) the thalweg will be approximately located in the center of the riverbed, but if the cross-section is more irregular (case of a pool), this will make the thalweg to move more towards one bank than the other. In the case of the Cabriel River, the thalweg was very divagating and it was located nearer of one bank, in most cases. This fact affects more the results obtained from distance than from elevation above thalweg.

(ii) the proper taxonomical identification of the species. All the specimens were determined at species level, except for *Tamarix* spp. Different species or even subspecies, varieties or hybridizations (not detected during field surveys) could perform differently and led to different results. Besides, other specimens could be of questionable origin (planted or weed-grown). Clonal plants present another problem. They grow as a set of connected shoots. However, the connections may be buried, so it is impossible to distinguish the complete individual (the genet) (Bullock, 2006). In all these cases, only genetic analysis could clarify their origin, which may lead to a more extensive data collection. Hence, we can assume that the level achieved in the field surveys was the best available approximation, given the time and resources available.

(iii) The sites of this study might be not completely comparable because they were located at different altitudes and latitudes, as explained before. However, it is something common that most of the natural sites are located in the headwaters where there is less human intervention, while the sites in the lowlands are mostly flow-altered (Suárez *et al.*, 2002; Palma *et al.*, 2009). It was not possible to find a natural (unregulated) site in the lowlands to implement this study.

(iv) Since the riparian zone is highly variable in terms of soils, the soil survey was designed to cover and summarize as much as possible all the soil variability but in a simplified way. Despite this simplification, some trends for the different riparian species were found.

(v) Although an overlapping was clear among species for all of the variables, it was possible to define groups of species. Nevertheless, the components of these groups depended on the trimming percentage and significance level applied in each case.

2.7.5 Management implications and further research

The methodology applied in this study has proved to be suitable to measure the regulation effects upon woody riparian species; therefore, it could be applicable to inform water management decisions involving changes in flow regime. Thus, community indices (such as richness) as well as the ranges of distribution of a certain key species in natural conditions, and the deviation from those 'reference values' could be further analysed to quantify the status of a water body in terms of its woody riparian species (Pont *et al.*, 2006). Apart from testing regulation effects, this methodology could be useful to test the effects of the global change in unregulated sites where a reduction in the water inflow has taken place. In the same way, the riparian species, which are long-term bioindicators, could be responding to the reduction of natural disturbances by means of a modification in their positional patterns.

Another possible use of the information provided by this study could be the application of the ranges of distances and elevation preferred by the species to design plantation modules when it is necessary to combine species with similar characteristics in rehabilitation projects taking place in the studied area.

Although the relation between abundance and cover gave a good estimation of the development stage of the riparian vegetation, an improvement of that estimation could be achieved developing growth curves for the key riparian species. i.e., curves relating height and/or diameter at breast height with the age of the plant. This dendrochronological approach would led to determining specifically the time span of each plant in the study reaches and therefore, it would let us know the hydrological time series under which each plant was established (recruited) and developed.

Using hydrological variables instead of morphological ones could be an additional further improvement. Response curves of hydrological variables could be developed for woody riparian species with a one-dimensional hydraulic model in each study reach and the aforementioned dendrochronological information. These curves could represent the typical inundation duration of each species, inundation frequency, etc. This could help in the definition of hydrological groups of riparian species and their associated preference curves.

Another possible improvement in this study could be achieved using the base flow as a reference instead of the thalweg. This river stage is more ecologically meaningful, because the base flow is considered as a reference for the survival and maintenance of the riparian vegetation, with special emphasis in Mediterranean environments, where the most limiting conditions take place during summer in form of low flows and/or droughts. In addition to this, using the base flow instead of the thalweg would reduce the uncertainties associated to the specific topography of the cross-sections in the definition of groups.

Chapter 3

Response curves and hydrological guilds of woody riparian species, oriented to water management in Mediterranean rivers

3 RESPONSE CURVES AND HYDROLOGICAL GUILDS OF WOODY RIPARIAN SPECIES, ORIENTED TO WATER MANAGEMENT IN MEDITERRANEAN RIVERS

3.1 ABSTRACT

Riparian vegetation is an essential component of fluvial ecosystems but low attention has been paid to their flow requirements and although it has been established as a key issue in the legislation at European, national and regional levels, basic information is still needed to fully incorporate it to the environmental flow assessments. To conduct a pilot study in this direction, two free-flowing Mediterranean reaches in nearly natural conditions and with high riparian quality were selected within the Júcar River Basin District (Eastern Spain). Coupling a hydraulic model with a geo-referenced survey of woody riparian species, along with a dendrochronological sampling, allowed us to obtain the time series of water elevations at which every single plant had been exposed during its lifetime. Five hydrological variables were considered (inundation duration, inundation duration during the growth period, continuous inundation duration, inundation frequency and plant elevation above base flow). The main species were compared, in order to assess a possible aggregation of them into functional groups or hydrological guilds. Response curves for each species and study site were constructed and compared among the species with the largest sample size. The differences were discussed by species and sites, based on the physical habitat conditions. An interpretation of the factors affecting the quality and uncertainty of the results was also included. The results are relevant to integrate riparian vegetation into water management decisions, especially through the assessment of environmental flow regimes in Mediterranean rivers.

Keywords: Riparian vegetation, response curves, functional groups, hydrological guilds, Mediterranean rivers, Júcar River basin.

3.2 INTRODUCTION

Riparian areas are very important in semiarid regions, which is the situation of most Mediterranean basins in Eastern Spain. Their habitats are characterized by a high level of biodiversity, due to the interactions of morphological and biological processes in terrestrial and aquatic ecosystems (Stella *et al.*, 2012).

Flow variability is one of the main factors controlling the morphological processes and the habitat availability for seedlings establishment, as it is recognized in multiple scientific studies (Richards *et al.*, 2002). Other authors have remarked that under natural conditions the zonation and species composition of riparian woodlands is to a large extend determined by hydrological conditions (Blom and Voesenek, 1996), especially flooding (Ward *et al.*, 2002). Other relevant aspects such as the moisture content and the position of the groundwater table are determined as well by the hydrologic regime of the river (Richards *et al.*, 1996; Hughes and Richards, 2003), that depends on the hydrology of the basin and the modifications introduced by the human through the construction of reservoirs. Besides, the frequency and magnitude of floods are crucial in the development of the riparian vegetation (Tabacchi *et al.*, 1998), as they generate abrupt breaks in the growth for the dragging of part or the entire plant mass.

Despite the importance of the riparian ecosystems, they are suffering an important degradation, because many processes are altered by human activities. Spain is one of the countries with the greatest number of large dams per inhabitant in the world (World Commission on Dams, 2000), and flow regulation has reduced the frequency and duration of extreme hydrological events in the riparian environment, such as high flows, reducing its conservation status. The present situation of a part of the Spanish riparian areas is bad (Ibero *et al.*, 1996). Multiple factors (agriculture, channelization, urbanization, transport networks, pollution, livestock concentration, etc.) have generated this situation, resulting in a deterioration of the structure and functionality of these ecosystems. In this sense, the reduction in the flow magnitude as well as the modification in the frequency and intensity of floods has been declared as one of the main factors limiting the natural regeneration of the riparian forests. Therefore, restoration plans should give freedom to the river and provide it with adequate flows to improve its functioning, the connection with the floodplain and the continuity of the ecological processes that take place in it.

These ideas have been compiled into the Júcar River Basin Management Plan (CHJ, 1998). In its article 19, related to flows and water volumes required for environmental reasons, it is stated *'as ecological or environmental flow is considered that flow able to maintain and recover the typical ecosystems of each river reach. This flow, specified within a flow regime, will be established using individual studies for each reach with hydrological and biological criteria, having into consideration the specific characteristics of both the ecosystem and the river. Furthermore, the annual volume required and the time variation of the minimum flows required for the proper functioning of the hydrosystem will be considered depending on the needs of protection (variable throughout the year) of the fauna and flora of each reach'*. According to the same article, in its section 2, *'the maintenance of an environmental flow is considered as a priority in the following cases: a) Species or habitats protected by national or regional legislation; b) Habitats or species listed in Annexes I or II of Directive 92/43/EEC, related to the conservation of habitats and wild flora and fauna: c) Valuable natural areas determined by the Environmental Administration, with special attention to singular cases of riparian forests; […]; e) Affection to wetland areas or fluvial reaches of environmental interest (related with the articles 75 and 76)'*.

Similarly and most recently, the law 11/2005 of 22 June, which modifies the Law 10/2001, of 5 July, about the National Hydrological Plan, in its article 42 establishes: *'For the allocation and reserve of hydric resources for present and future uses and demands, as well as for the conservation and recovery of the natural environment, will be determined: a) The environmental flows, defined as those able to maintain at least the fish life that naturally inhabit or could inhabit the river and its riparian vegetation; b) The fluvial nature reserves, in order to preserve, unaltered, those stretches of rivers with little or no human intervention. These reserves shall be limited strictly to the hydraulic public domain.'*

As stated earlier, the hydrological and hydraulic conditions in a river segment are the main drivers of the morphological processes, and hence the presence of recruitment and the distribution of riparian species; therefore it is possible to observe a spatial pattern of species along a gradient approximately perpendicular to flow in relation to the species response to the physical conditions. The positional patterns of the different species have been studied, but in some cases without a quantitative assessment of the hydrological gradients controlling such patterns.

In this sense, the definition of guilds has been highlighted in literature as a useful way to manage species with similar traits and therefore that respond similarly to the physical habitat conditions (see Merritt *et al.*, 2010). This approach has been applied to different components of the fluvial ecosystem, such as birds and mammals (Croonquist and Brooks, 1991), macroinvertebrates (Luczkovich *et al.*, 2002), fish (Aarts and Nienhuis, 2003) and more recently to riparian species (Merritt *et al.*, 2010; Bejarano *et al.*, 2012a).

We hypothesized that the assessment of how riparian species change in response to environmental conditions with a response-guild approach can be more efficient and transferable across regions. Furthermore, the different position of guilds and their variability in the transversal gradient may reflect their different sensitivity to both natural and human disturbances. Furthermore, the quantitative assessment of the hydrological gradients controlling vegetation patterns with a response-guild approach could help in the integration of the riparian vegetation into the water management decision-making in Mediterranean rivers.

Therefore, the main objective of this research was to study the relation between target woody riparian species and the flow regime, through the development of response curves and guilds of hydrological response. The specific objectives of this study were:

A. To carry out hydrometry measurements and hydraulic modelling of the study reaches and a geo-referenced survey of vegetation coupled with the hydraulic model.

B. To conduct a dendrochronological survey of target woody riparian species and develop growth functions in order to estimate the age of all the specimens surveyed in the field.

C. To define hydrological response variables.

D. To develop response curves for each one of the hydrological response variables for target woody riparian species, to compare between species and define guilds of hydrological response.

3.3 STUDY SITES

Two study sites were selected in free-flowing segments of Mediterranean rivers within the Júcar River Basin District (Eastern Spain) (**Figure 3.1**). The first study site, known as 'Terde' (hereafter, MTE), was located in the Mijares River, near the village of Sarrión (Teruel province); the second site, known as 'Rabo del Batán' (hereafter, CRA), was located in the Cabriel River, near Carboneras de Guadazaón (Cuenca province).

These reaches were selected because their availability of long data series of hydrological records and good conservation status (nearly-natural conditions). The selection was based on aerial photographs and field observation.

According to the ecological typologies defined by the Spanish Ministry of Environment (CEDEX, 2004; CHJ, 2009b), both study sites belong to the ecotype 12, named as '*rivers in calcareous Mediterranean mountain*'. The Strahler stream order is 3 in the site CRA and 2 in MTE, what can be translated into higher flows and higher accumulated basin area in the first site than in the second (**Figure 3.2** and **Figure 3.3**).

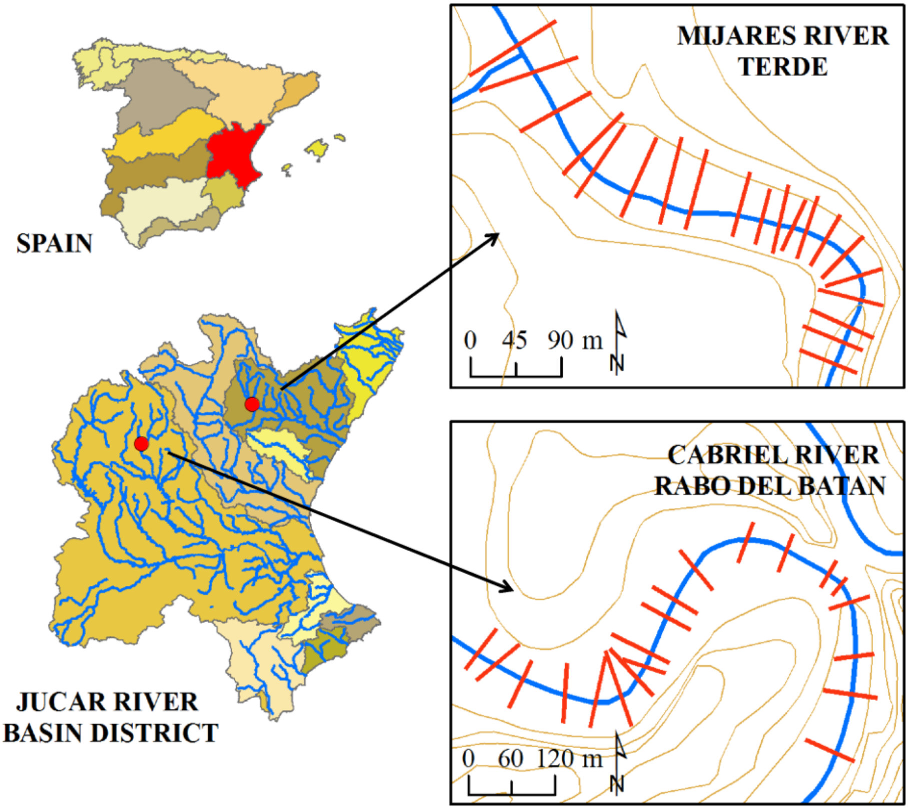


Figure 3.1. *Location of the free-flowing study sites within the Júcar River Basin District (Eastern Spain). The twenty cross-sections for each site are shown in red colour.*

3.3.1 Hydrological characterization

The Cabriel River is one of the most important rivers in Eastern Spain. It rises at 1620 m above sea level in Muela de San Juán (Teruel province) and flows 220 km in a north-south direction to its confluence with the Júcar River in Cofrentes (Valencia province). Its basin area is 4754 km^2. It shows low magnitude floods in spring and larger floods in autumn, usually between October and November. The summer is normally a period of low-flow.

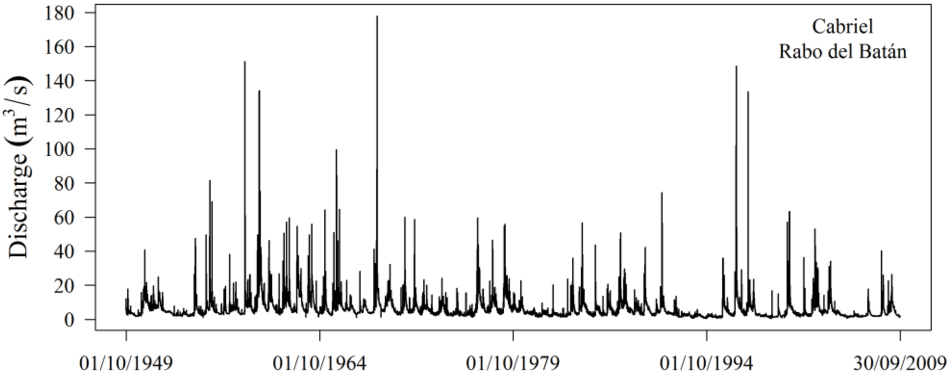


Figure 3.2. *Daily river discharges (m^3/s) in the Cabriel-Rabo del Batán reach (CRA). Period: 1949-2009.*

The site CRA is located at 925 m above sea level. It is 910 m long and its catchment area is 962.60 km^2. The distance from the river source to the site is 93.47 km. Its mean annual discharge is 5 m^3/s. The site is located downstream of the Cristinas weir. The gauging data in this site comes from the station of Pajaroncillo (CEDEX), located only 3421 m upstream of the study site. The watershed area at the site differs in 132 km^2 in relation to the watershed area at the gauging station and an ephemeral tributary (Rambla de las Posadas) intercepts the main river stem between both points (site and gauging station). Therefore we considered that a correction was necessary in order to represent more accurately the flow regime at the site. The daily river discharges are represented in **Figure 3.2** and the characteristics of the gauging station are listed in **Table 3.1**.

Table 3.1. *Main characteristics of the flow gauging stations at the Cabriel and Mijares rivers.*

Gauging Station	Code	X-Y UTM	Catchment area (km^2)	Level (m)	Location (from site)	Period
Pajaroncillo	8090	610230-4422140	829	940	Upstream	1949-Present
Terde	8030	689692-4448508	665	845	Downstream	1945-Present

The Mijares River has its source in the Sierra de Gúdar (Teruel province) at 1600 m above sea level. It flows 156 km from NO to SE until its mouth in the Mediterranean Sea. The stream flow pattern is determined by rainfall and secondly by snow, with notable intra-annual and inter-annual variability in the discharge, characteristic in Mediterranean watersheds; 11 ºC is the average annual temperature and 500 mm the average annual precipitation. The total basin area is 5466 km^2.

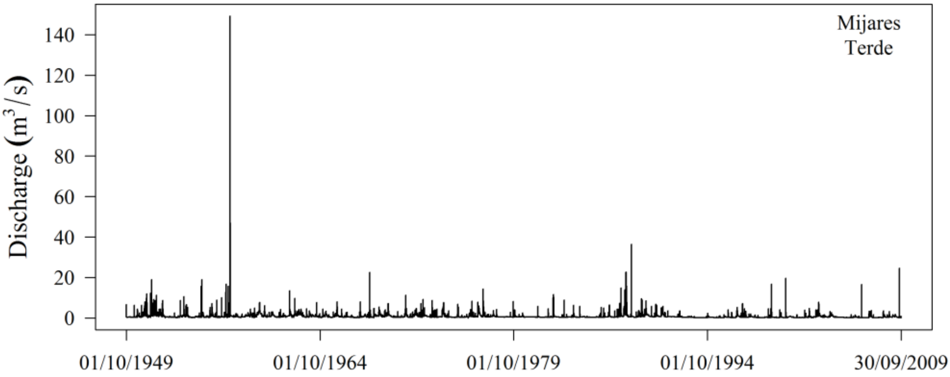


Figure 3.3. *Daily river discharges (m^3/s) in the Mijares-Terde reach (MTE). Period: 1949-2009.*

The site MTE is located at 850 m above sea level, its length is 539 m and its catchment area is 665 km^2. The distance from the river source to the site is 43 km. Its mean annual discharge is 0.9 m^3/s. The gauging data in this site comes from the station 'Terde' (CEDEX), located in the town of Sarrión, only 550 m downstream of the study site. The watershed area is very similar and there are no tributaries or springs between site and station, therefore no correction was necessary. The daily river discharges are represented in **Figure 3.3** and the characteristics of the gauging station are listed in **Table 3.1**.

As can be seen, both sites have long hydrological data series (since late forties to present). The characteristics of the flow time series of the gauging stations at the Cabriel and Mijares River are shown in **Table 3.2** (information available online at the CEDEX's website: http://hercules.cedex.es/anuarioaforos). The coefficient of variation of annual flows is calculated as the standard deviation of the mean annual flow for the complete data series divided by the arithmetic mean of the mean annual flows series.

Table 3.2. *Characteristics of the flow time series (m^3/s) of the gauging stations at the Cabriel and Mijares River.*

Gauging Station	Mean annual flow	Min. annual flow	Max. annual flow	Min. monthly flow	Max. monthly flow	Annual coefficient of variation
Pajaroncillo	5.091	0.91	13.67	0.52	39.11	0.54
Terde	0.886	0.16	2.29	0.10	18.33	0.56

In the next figure are shown the curves of probability of exceedance for both sites for the common period 01/10/1949-30/09/2009. Exceedance probability is the probability that a certain value is going to be exceeded.

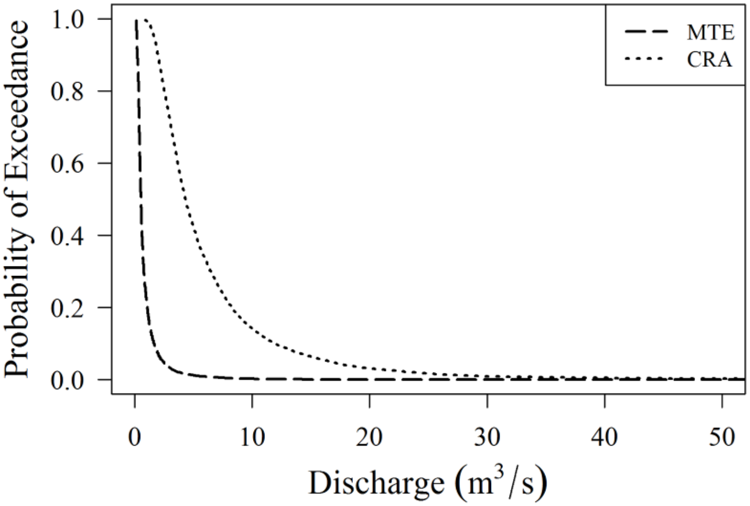


Figure 3.4. *Probability of exceedance for both study reaches, Mijares-Terde (MTE) and Cabriel-Rabo del Batán (CRA). Horizontal axis is limited to 50 m^3/s to improve visualization. Period 01/10/1949 - 30/09/2009.*

As illustrated in **Figure 3.4**, for a given probability of exceedance, the discharges in CRA are larger than in MTE. For example, the probability that discharges of 5, 10 and 20 m^3/s are exceeded is 42 %, 14 % and 3 % in CRA, and 1 %, 0 % and 0 % in MTE, respectively. The maximum daily flow registered in Terde was 149.15 m^3/s (13/10/1957) and 177.82 m^3/s in Pajaroncillo (17/03/1969).

3.3.2 Riverine characterization

Apart from the flow data availability, the second aspect that influenced the selection of these reaches was their good riparian quality and high plant diversity. In both sites the connectivity of the riparian forest with the upland terrestrial forest is complete.

Riffles and glides are the dominant hydromorphological units in the river channel at CRA, although a big pool is also present in the upstream section of the reach. The substrate of both riverbed and floodplain is mainly composed of sand. The deposition areas, only covered with water during floods, are composed by coarser substrate, mainly cobbles (ø 64-256 mm) in a matrix of gravel (ø 8-64 mm) and fine gravel (ø 2-8 mm). In two sections of the reach (right bank downstream and left bank upstream) there were secondary channels where water only flows in exceptional high-flow events.

The riparian forest is composed by specimens of Salicaceae family, both in the shrub and tree layer, that densely cover both riverbanks, with some alternating habitats dominated by reed communities (*Scirpus* and *Phragmites*). The shrub layer dominating the bank zone is composed by *Salix purpurea*, *Salix eleagnos* and *Salix triandra*. The tree layer dominating the bank and floodplain zone is composed by *Fraxinus angustifolia*, *Salix alba*, *Populus alba* and *Populus nigra* accompanied by exemplars of *Crataegus monogyna*. The terrestrial vegetation is mainly composed by trees of the genus *Pinus*. In shallow margins, reed communities (e.g., *Phragmites, Sparganium, Thypa*, etc.) dominate. The natural riparian formations composed of willows, ashes and poplars are protected by the red list of Castilla La Mancha region. For more information about the species abundance, cover and density, see Chapter 1.

The riparian quality of CRA is very high, as revealed by the protocols assessed. According to the Riparian Habitat Quality Index – QBR (Munné *et al.*, 2003), the site got the maximum punctuation, 100 points (out of 100), revealing a quality class 'Excellent' and therefore a riparian corridor in natural conditions. The assessment of the Riparian Quality Index – RQI (González del Tánago *et al.*, 2006), revealed a riparian status 'Good' (101 points out of 150), meaning that most of the attributes are in good or very good conditions and one or two can be altered, like the condition of the banks (presence of a lateral structure to protect a road) and the infiltration capacity of the substratum (some compacted areas due to cattle grazing).

Figure 3.5. *Photographs illustrating the upstream (a) and downstream (b) sections of the Cabriel-Rabo del Batán (CRA) study reach.*

In the case of MTE, the dimension of the floodplain is smaller and in some areas the sediment bars are mobile. Riffles are abundant. The substrate is diverse, including fine gravel (ø 2-8 mm), gravel (ø 8-64 mm) and cobbles (ø 64-256 mm) as the predominant substrate, with some scattered boulders (ø 256-1024 mm) in different areas of the reach. There are multiple elements of heterogeneity in the site and secondary channels where water flows throughout the year. The slopes are steep in some parts. Some abandoned terraces could have been cultivated in the past. The connectivity between the riparian and terrestrial forest is almost complete. The riparian forest covers about 75 % of the riparian corridor, alternating with bedrock areas, boulders and alluvial deposits free of vegetation.

The riparian community comprises *Salix purpurea*, *Salix eleagnos*, with less abundant *Populus nigra*, *Salix alba* and *Salix atrocinerea*. There are also reed communities (mainly composed of *Phragmites australis*) in the wetter areas of the site. The terrestrial forest is composed of *Juniper* spp., *Quercus coccifera* and *Quercus ilex*.

The site MTE was considered as one of the most natural, dynamic and diverse sites of the Júcar River Basin District, in comparison with other sites visited during the selection of the sites. We considered that the site is in a good quality status due to the presence of stands of different ages and abundant recruitment of pioneer species. According to the riparian quality index QBR (Munné *et al.*, 2003), it got 85 points out of 100, revealing a quality class 'Good'. The assessment of the Riparian Quality Index – RQI (González del Tánago *et al.*, 2006), revealed a riparian status 'Good' (102 points out of 150), meaning that most of the attributes are in good or very good conditions.

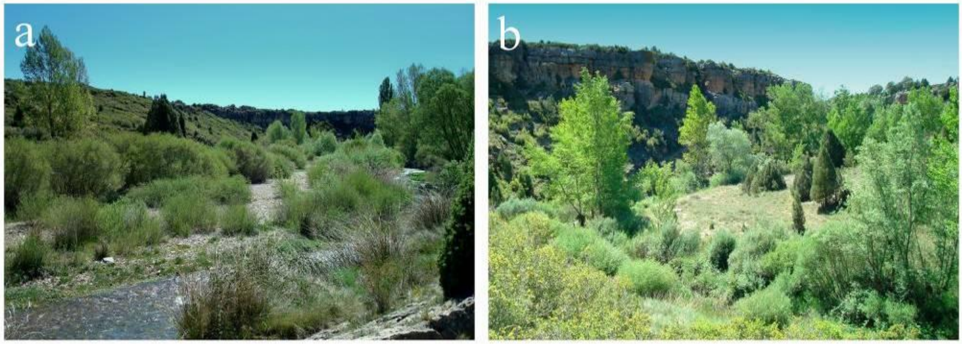


Figure 3.6. *Photographs illustrating the upstream (a) and downstream (b) sections of the Mijares-Terde (MTE) study reach.*

3.4 METHODS

3.4.1 Geo-referenced sampling of vegetation by transects

A geo-referenced survey of vegetation was performed along cross-sections perpendicular to the stream flow to study the spatial distribution (location and elevation above water surface) of the main woody riparian species. Each cross-section was marked out with one steel rod in every riverbank (**Figure 3.7 a**), in order to have fixed references for successive field campaigns. Two points per vegetation unit were recorded along the cross-sections using a GPS in areas with good signal and a total station in densely vegetated areas (**Figure 3.7 b**). For a detail description of the protocol followed in the field, see Chapter 1.

Two codes were assigned to each vegetation unit. For example, *02PA1i* and *02PA1f*, meaning the beginning (*i*) and end (*f*) points of the first vegetation unit of white poplar (*Populus alba* L.) recorded in transect number two.

Figure 3.7. *Example of a steel rod marking out the location of one cross-section (a) and geo-referenced survey of vegetation units in CRA using a total station (b).*

In **Figure 3.8** and **Figure 3.9** can be seen the aerial photographs of the reaches and the location of the cross-sections and steel rods.

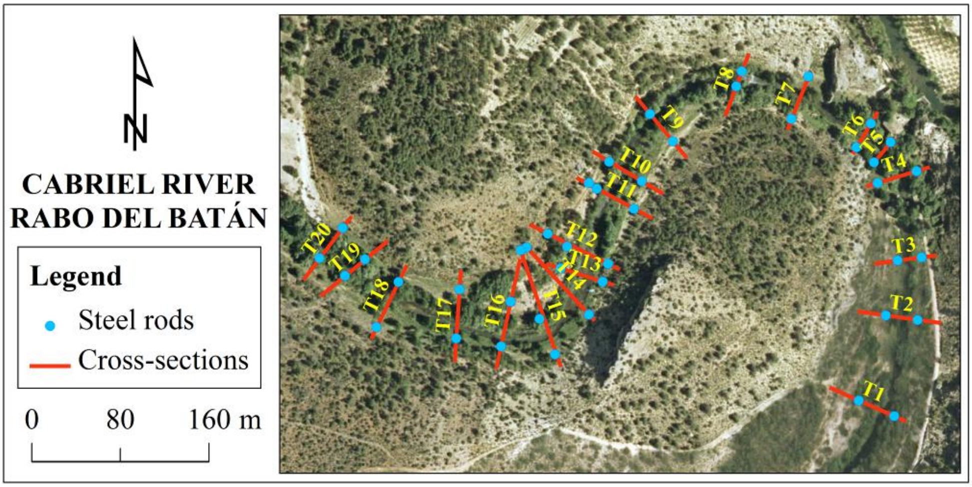


Figure 3.8. *Cross-sections and steel rods in Cabriel-Rabo del Batán (CRA).*

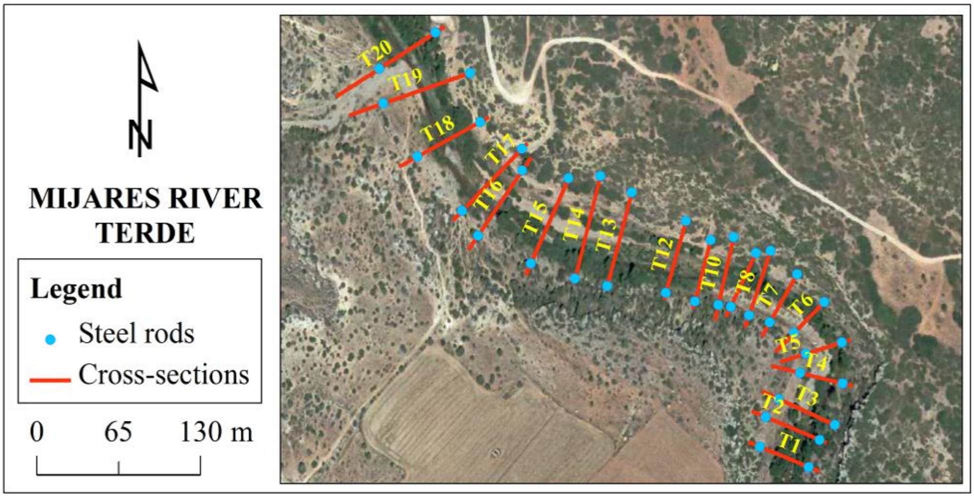


Figure 3.9. *Cross-sections and steel rods in Mijares-Terde (MTE).*

3.4.2 Dendrometric survey

Several measurements were recorded for each one of the specimens geo-referenced in the field survey. The height of the trees and shrubs was measured using an electronic clinometer Haglöf® (resolution 0.1 m and ± 0.2°), which allowed measuring the height at whatever known distance from the individual we were located. The diameter at breast height (DBH, at 50 cm from the ground for shrubs and 130 cm for trees) and diameter at ground level (DGL) were recorded using an aluminium calliper (resolution 0.001 m). When the trunk was symmetric (similar to a circle) one measure was taken, but when the trunk was more asymmetric, two measures were taken and averaged later on (**Figure 3.10**).

Figure 3.10. *Measurement of the diameter at ground level (a) and diameter at breast height (b) using a caliper, and measurement of the height of a tree, using a measuring tape to set the distance (c) and an electronic clinometer (d).*

Some specimens of the target woody riparian species were selected for the age estimation. They were chosen from the widest age range possible, from small saplings to old trees. As can be seen in **Figure 3.11 b**, core samples were taken from adult specimens using an increment borer (also known as Pressler drill). In small specimens, sections were obtained using pruning shears. The selected trees and shrubs were located within the limits of the sites and in their respective surrounding areas.

Figure 3.11. *Code system used to identify the vegetation units in the field (a) and core samples extraction using increment borers (b).*

3.4.3 Core samples preparation and definition of growth functions

After collection in the field, the cores were mounted and tied on wooden mounts of the same diameter (5 mm) and kept in filter paper bags for transportation. They were dried overnight in the laboratory and the next morning they were glued to the wooden mounts and finely sanded using a DREMEL® and sandpapers of different grain size.

Sanding made possible to increase the visibility of the annual growth rings and therefore, it was possible to assign a number of years to each sample. The counting of growth rings was performed using a binocular microscope and the results were noted on a form. As in most cases two samples were taken in each tree, perpendicular to each other (increasing the chances of passing through the pith of the tree), this helped to estimate the tree age more accurately. In samples where central rings were not reached by the increment borer, the estimation was done using the curvature of the central rings and other samples of nearby specimens of the same species.

This information, along with the rest of the dendrometric information, was useful to develop growth curves by species. Initially, a different curve was obtained for each site and species. A new curve was generated for a few species gathering the data from both sites, when the sample size was small or the curves of both sites were very similar. To do so, we looked for a similar trend, not having a distance larger than 5 years between the curves of both sites. According to Ferry (2010), a dating accuracy of 5 years can be considered acceptable. Determining the exact age of a specimen is a difficult task as it depends on where the core was extracted i.e., position in the trunk, if the pith was reached or not and the location and environmental conditions of the stand. Those conditions, such as erosion, uprooting and water stress can promote the formation of absent, faint and false rings. Therefore, in our opinion, a dating accuracy of 5 years can be considered as a consistent criterion for gathering two curves. Finally, the relations obtained were used to estimate the age of all the plants recorded in the inventory and therefore to calculate the lifetime period of each plant.

Figure 3.12. *Sandpaper of different grain size and cores of three samples taken in Cabriel-Rabo del Batán (a). Counting of growth rings using a binocular microscope (b).*

3.4.4 Hydrometry

At each site, hydrometry campaigns were carried out. We used the same cross-sections used to record the position of the vegetation units to have a representation of the topographic conditions (profile of the river bed, banks and floodplain). This information was necessary to build and calibrate a 1-dimensional hydraulic model.

The quality and hydraulic properties of the first cross-section downstream were taken into consideration when the sites were selected and delimited. It was important from the hydraulic modelling point of view to have permanent and uniform regime at the beginning and at the end of the site (and if possible, at hydraulics controls). For this reason, sections with very slow water, aquatic vegetation or high turbulence were discarded. Apart from the biotic requirements (presence of vegetation units), the cross-sections were located in relevant changes of the water surface profile.

The water surface elevation in both banks was recorded using the topographic equipment. To measure the hydraulic conditions and to estimate the flow rate at the specific moment when the water level was recorded, we used the area-velocity method. This method uses a classical hydraulic equation to calculate the flow (1.), in a cross-section with area *A*. This equation is calculated approaching the integral, by means of the sum of the partial flows calculated for *i* virtual cells in which the transverse area is divided, *i* = 1, 2… *n*, of wide Δ*wi*, average velocity *Vi* y depth *Di*. Therefore, the flow is calculated like the formula (2.).

$$Q = \int_A V \cdot dA \tag{1.}$$

$$Q = \sum_{i=1}^{n} V_i D_i \Delta w_i \tag{2.}$$

The number of measurements depended on the width of the water surface and the topographical irregularity of the riverbed, and it was done to represent the topography of the cross-section. The depth *Di* was recorded in each cell with precision of 1 cm, with a graduated rod. The average water velocity *Vi* in each cell was measured in perpendicular direction to the cross-section using an electromagnetic current meter (VALEPORT 801®) of precision 0.001 m/s. The time of measuring the velocity in each cell was 15 seconds.

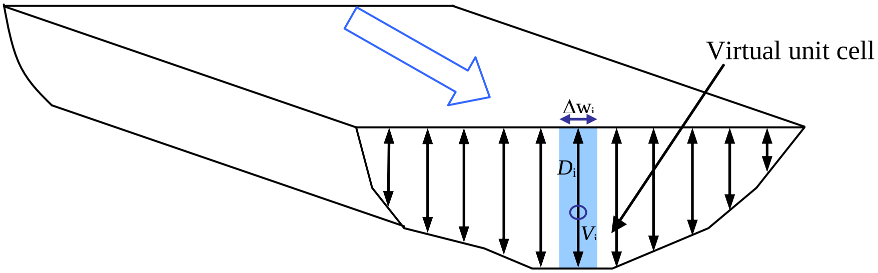


Figure 3.13. *Area-velocity method to estimate the flow in a river cross-section.*

The points to measure velocity were the same where depth was measured; the number of points in the water column necessary to estimate the mean column velocity depends on the depth and other conditions that can produce an anomalous velocity profile (turbulence, coarse substrate, obstacles, etc.). When depth was equal to or less than 0.45 m, the velocity was measured at 60 % of the water depth (from the surface). When depth was between 0.45 and 0.80 m, two measurements were made at 20 % and 80 % of the depth, so the average velocity was obtained as the average of both velocities. When depth was larger than 0.80 m, velocity was measured at 20 %, 60 % and 80 % of the depth, calculating the average velocity of the cell as the average between the average of the velocities at 20 % and 80 % with the value measured at 60 %.

Apart from velocity and depth, each cell was characterized by the percentage composition of the dominant and co-dominant substrate classes, following the American Geophysical Union nomenclature but simplified (Martínez-Capel, 2000). In the evaluation of the substrate, the presence of aquatic vegetation in the riverbed and banks, as well as the presence of other elements able to modify the quality of the gauging, were written down.

Table 3.3. *Size classification of substrates according to their mean diameter following the American Geophysical Union nomenclature (Martínez-Capel, 2000).*

Substrate	Size range (mm)
Silt	< 62 μm
Sand	62 μm-2 mm
Fine gravel	2-8 mm
Gravel	8-64 mm
Cobbles	64-256 mm
Boulders	256-1024 mm
Big boulders	> 1024 mm
Bedrock	> 1024 mm continuum

The flow measurement was performed in the sections with better gauging quality (approximately permanent and uniform flow), stable substrate, no aquatic vegetation or helophytes and no turbulence. In **Table 3.4**, the flows gauged in each study reach are shown.

Table 3.4. *Flows gauged at both study sites that were used to obtain rating curves and in the hydraulic simulation.*

Site	Date	Flow (m^3/s)
Cabriel - Rabo del Batán	27/07/2009	1.057
Cabriel - Rabo del Batán	15/01/2010	44.908
Mijares - Terde	26/05/2009	0.468

It was necessary to do all the work (topography and hydrometry) in a short period of time (some hours) in order to have a reliable relation between the water surface at each cross-section and the average flow rate during the day.

3.4.5 Hydraulic modelling

The final objective of the hydraulic simulation was to obtain rating curves, also known as ‘flow-level curves’ or ‘stage-discharge curves’, which allow us to transform the flow time series into a level time series. Therefore, we were able to establish a relation between the flow regime and the water level in each river cross-section.

The flow gauged at the sites were necessary to calibrate the hydraulic models. In CRA, the simulations were performed with the software Rhyhabsim (Jowett, 1989) and in the case of the MTE with the software HEC-RAS (Brunner, 2008).

3.4.6 Definition of variables

Five variables were calculated for each vegetation unit based on the daily average flow records translated into a level time series. The variables selected are those considered as more meaningful in the literature that relate the presence of healthy riparian forest with the flow regime, as well as those publications concerning different methods of simulation of important variables for riparian vegetation, at scale of individuals, guilds or vegetation types (Merritt *et al.*, 2010).

We have worked with water years (i.e. from October of the present year to September of the following year) in order to make the results more understandable from the water management point of view. The variables selected were:

- *Inundation duration* (V1), as number of days per year that water covers the whole root system. The average data for each plant, during its lifetime period, was considered as an independent data for the analyses (same in the following variables). This variable is one of the most frequent in the study of hydrological responses of riparian vegetation. It is related with the capacity of the plant to tolerate anoxia; nevertheless, this phenomenon could be less important in free-flowing rivers located in arid and semi-arid areas due to water scarcity. The predictive value of this variable is mostly due to its correlation with other variables derived from the flow regime that also affect to the vegetation distribution, such as soil moisture, groundwater depth, shear stress and concentration of oxygen in the soil (Auble *et al.*, 1994).

The importance of the variable 'inundation duration' has been highlighted in the literature as different studies have shown that the riparian species and communities can be ordered according to it (Hupp and Osterkamp, 1985).

Also simple models have been used to describe the position of different vegetation types along the gradient defined by this variable (Harris, 1986; Auble *et al.*, 1994), in response curves for specific species (Auble *et al.*, 2005), as well as in more complex models at population level (Pearlstine *et al.*, 1985), using functional groups (Toner and Keddy, 1997) and vegetation classes (Primack, 2000).

- *Inundation duration (number of days per year) during growth period* (V2). The growing season was estimated, in this Mediterranean area, as the period of spring and summer, i.e. approximately 6 months.

Some authors have related this variable with the presence of woody cover (Toner and Keddy, 1997). Others have used specific flow variables for that period in their models (e.g. Stromberg, 1993).

The periods of growth and establishment of the plants are critic for their survival and the results can be more significant than the total inundation duration, as number of days per year. According to Vreugdenhil *et al.* (2006), with respect to the species composition, the whole-year data appears to have more explanatory power than the growing season data, but they found that flooding during growing season was shown to have more negative effects on the presence of hardwood species than during the entire year.

This variable could predict better functional groups or guilds of species and could be potentially related with the growth of a certain species in a site. It can be especially important in the first years after establishment, when some species can behave as obligate phreatophytic and others as facultative phreatophytic.

In temperate regions, the growth period is the part of the year when plants germinate, grow and produce flowers and fruits. In other words, it would be the time of the year when growth takes place and the plants reproduce. In **Table 3.5**, the temporal distribution of the flowering and the ripening of fruits and dispersal of seed for the target woody riparian species is estimated according to the Riparian Tree and Shrub Propagation Handbook for the Mediterranean Region (Aránzazu-Prada and Arizpe, 2008).

In a general sense, in the Mediterranean region the growth period coincides with the spring and summer (i.e. from March 21st to September 22nd). This is the period that has been considered to calculate the inundation duration during growth period, as can be seen in **Table 3.5**, all of the target species are finishing flowering, ripening and dispersing their seeds at that time and starting the establishment of the new seedlings.

Table 3.5. *Temporal distribution of the flowering and ripening phases of the growth period of the target woody riparian species.*

Scientific name	**Code**	**Phase**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Salix purpurea L.	SP	Flowering		░	░	░								
		Ripening				▓	▓	▓						
Salix alba L.	SL	Flowering	░	░	░									
		Ripening			▓	▓	▓							
Salix eleagnos Scop.	SE	Flowering	░	░	░									
		Ripening			▓	▓	▓							
Populus nigra L.	PN	Flowering		░	░	░								
		Ripening			▓	▓	▓	▓						
Populus alba L.	PA	Flowering		░	░	░								
		Ripening			▓	▓	▓	▓						

- *Continuous inundation duration* (V3), as average consecutive number of days per year when the whole root system is inundated.

It is related with the physiological threshold of the plant, and therefore it is of great interest to water management. It is considered here as a surrogate to the maximum tolerance to hypoxia. This is one of the key variables that change with irrigation water management, and also for hydroelectric production.

Continuous inundation duration has been one of the variables most used in studies about the effects of flooding in the distribution of plants (e.g.Toner and Keddy, 1997; Bauder, 2000; Richter and Richter, 2000).

- *Inundation frequency* (V4), as times per year that an independent hydrological event causes the inundation of the root system. The calculation of this variable involves estimating the flow that would cover the whole root system, and then calculate the number of separate floods that equal or exceed that value per year. The importance of this variable has been indicated by several studies (Merritt *et al.*, 2010), in the establishment of Salicaceae species (Cooper *et al.*, 2006) as well as in population models (Lytle and Merritt, 2004) and in more complex dynamic modelling, which use this variable to separate different areas in the floodplain using geographic information systems (Corenblit *et al.*, 2008)

- *Plant elevation above water elevation at base flow* (V5). Base flow is considered to be the ground-water contribution to stream flow (Arnold *et al.*, 1995) in a situation of dry weather, i.e., it is not attributable to direct runoff from precipitation (Kara *et al.*, 2012). Depending on the level of the aquifer, the base flow can change between dry, normal and wet years. In order to obtain a representative value for the entire study period, the base flow was calculated using the normal hydrological years (those years with an average flow between percentiles 25 and 75). The calculation was focused on the low-flow periods with a decreasing or maintained trend during that time.

Using the rating curves, the base flow was translated into a level for each cross-section. Then, the position of each vegetation unit in the cross-section was referred to the elevation above base flow.

This has been considered as one of the most important variables to know how the different riparian species distribute spatially in the riparian zone (Camporeale and Ridolfi, 2006). Harner and Stanford (2003) used this variable, among others, in the study of the difference in growth of *Populus* sp. It has been also used to study the establishment patterns of other woody species (Cooper *et al.*, 2003).

3.4.7 Data analysis

Only the species with relevant sample size (N>28) were further analyzed. The information for each site and variable was summarized in a boxplot. The Huber estimator (robust estimate of location that reduces the effects of the outliers) was calculated for each species using the R package *mass* (Venables and Ripley, 2002).

A robust analysis of variance was carried out (robust Welch one-way ANOVA) to contrast the null hypothesis of equality of means for all the woody riparian species in relation to the hydrological variables. This test is much more reliable than a standard one-way ANOVA when the normality and variance homogeneity assumptions are violated. When the null hypothesis was rejected, a test for multiple comparisons was applied to define groups of species with the same response in relation to the variables analysed (Wilcox, 2012). The significance level applied was 0.05 and the trimming percentage 20 %.

Only those species with sample size higher than 75 individuals were considered for the definition of response curves. Each value was rounded up to the next integer number. For example, when the inundation duration was 4.62 days, this value was rounded to the nearest higher number, i.e. in this case to 5 days.

A frequency histogram was developed with the raw information. The intervals of evaluation were different for each variable and species. The optimum number of classes (k) of each histogram (able to catch the data structure) was determined as $\sqrt{n}$ (square-root choice; Maciejewski, 2011), being n the total sample size. An envelope curve was defined with the normalized frequencies i.e., transforming them into a range 0-1, assigning the number 1 to the class with the largest number of counts. This curve was shown in the same graph as a habitat suitability index. To fill the gaps due to the lack of data in certain intervals, we used the criteria of maintaining suitability index not smaller than 0.2. The kernel density estimation was used for data smoothing using a Gaussian method, included in the R package *stats* (R Development Core Team, 2010).

3.5 RESULTS

Among all the woody riparian species recorded in the fieldwork, only those with larger sample size were analyzed. This information is summarized in **Table 3.6**.

Table 3.6. *Sample size of the woody riparian species in each study site, and species' codes.*

Scientific name	Code	Cabriel River (N)	Mijares River (N)
Populus alba L.	PA	294	0
Populus nigra L.	PN	116	110
Salix alba L.	SL	34	28
Salix eleagnos Scop.	SE	75	46
Salix purpurea L.	SP	76	178

3.5.1 Growth functions

In the following two tables are shown the growth functions obtained for each target woody riparian species and site. They have been used to estimate the age of all of the vegetation units sampled in the geo-referenced survey.

Table 3.7. *Growth functions (and their respective coefficients of determination) of the target species in Mijares-Terde (MTE). Both sample sizes, the one collected in the site and the one used to create the curves (in parenthesis) are shown.*

Scientific name	**N**	**Growth function**	**R^2**
Populus nigra L.	31 (31)	AGE = 0.953 * (HEIGHT) + 1.469	0.936
Salix alba L.	12 (19)	AGE = 0.592 * (DBH130) + 5.925	0.918
Salix eleagnos Scop.	22 (22)	AGE = 1.214 * (DGL) + 3.73	0.754
Salix purpurea L.	26 (32)	AGE = 2.034 * (DGL) + 1.439	0.800

Table 3.8. *Growth functions (and their respective coefficients of determination) of the target species in Cabriel-Rabo del Batán (CRA). Both sample sizes, the one collected in the site and the one used to create the curves (in parenthesis) are shown.*

Scientific name	**N**	**Growth function**	**R^2**
Populus alba L.	20 (54)	AGE = 0.748 * (DBH130) + 5.928	0.837
Populus nigra L.	11 (11)	Height < 1.3 m → AGE = 0.953 * (HEIGHT) + 1.469 Height > 1.3 m → AGE = 0.330 * (DBH130) + 23.848	0.936 0.268
Salix alba L.	7 (19)	AGE = 0.592 * (DBH130) + 5.925	0.918
Salix eleagnos Scop.	6 (6)	AGE = 5.406 * (HEIGHT) + 0.079	0.955
Salix purpurea L.	6 (32)	AGE = 2.040 * (DGL) + 1.439	0.800

For *Populus nigra*, a different growth curve was created for each site. At MTE, the curve applied to individuals of all sizes was that relating AGE-HEIGHT. For CRA, the curve AGE-DBH was used, despite of having the curve AGE-HEIGTH a better adjustment but it did not define well the smaller individuals (height < 1.30 m). The age of those was calculated with the curve AGE-HEIGHT from MTE.

In the case of *Populus alba*, it was only present in CRA (N = 20). With the aim of increasing its sample size and making the curve more robust, we created a new curve adding data from the same species coming from a site in the Serpis

River (N = 34) surveyed within the Ribera Project (Francés *et al.*, 2009). The curves from both sites were quite similar [CRA: AGE = 0.786 (DBH130) + 8.351; R^2 = 0.798], [Serpis: AGE = 0.667 (DBH130) + 4.774; R^2 = 0.885], but putting all data together the coefficient of determination improved, as can be seen in **Table 3.8**.

For *Salix alba*, we opted for gathering the data coming from both sites because they have a small sample size on their own and their curves actually were very similar [MTE: AGE = 0.620 * (DBH130) + 5.151; R^2 = 0.878] [CRA: AGE = 0.457 * (DBH130) + 12.767; R^2 = 0.787]. The coefficient of determination improved with pooled data.

Similarly, for *Salix purpurea*, we decided to gather the data coming from both natural study sites [MTE: AGE = 1.943 * (DGL) + 1.510; R^2 = 0.834] [CRA: AGE = 2.256 * (DGL) + 1.723; R^2 = 0.790] in order to create a unique curve. In this case, the curves were created with the diameter at ground level and adding the point 0 years – 0 DGL.

For *Salix eleagnos*, different curves were used in each site. In CRA the sample size was small. We used the curve AGE-HEIGHT introducing the data 0 years – 0 height to improve the adjustment. In MTE, the curve AGE-DGL was selected instead, for having the better adjustment and being more meaningful for a shrub species (continuous flooding can limit its growth in height, therefore the diameter at ground level can perform better). Gathering data from both sites (N = 28) did not improve the adjustment in this case.

3.5.2 Boxplots of hydrological variables and definition of hydrological guilds

Data distribution for the species mentioned above was compared using boxplots, to assess a possible aggregation of species into functional groups or hydrological guilds. As can be seen in several figures, outliers were more abundant for some variables than for others; however, the parameters were the same for all the tests. As a general rule, groups were more evident in CRA than in MTE. In the following paragraphs the response of each species in each site for each variable is described.

Significant differences in the inundation duration (hereafter, V1) of the riparian species were detected at CRA (**Figure 3.14 left**) ($FW_e = 29.80$; $p = 0.000$). The multiple comparisons showed 3 groups of species: [SL-SP], [PN] and [PA-SE]. Relating to the Huber estimator, SP and SL exhibited values hovering around 180 days of inundation, PN 62 days, SE 9 days and PA only 2 days a year. As can be seen in **Figure 3.14** (**right**), in the case of MTE, the species did not show differences. Relating to the Huber estimator, all the species exhibited values between 0 and 1 days (SL = 0.6; SP = 0.5; SE = 0.4; PN = 0.4).

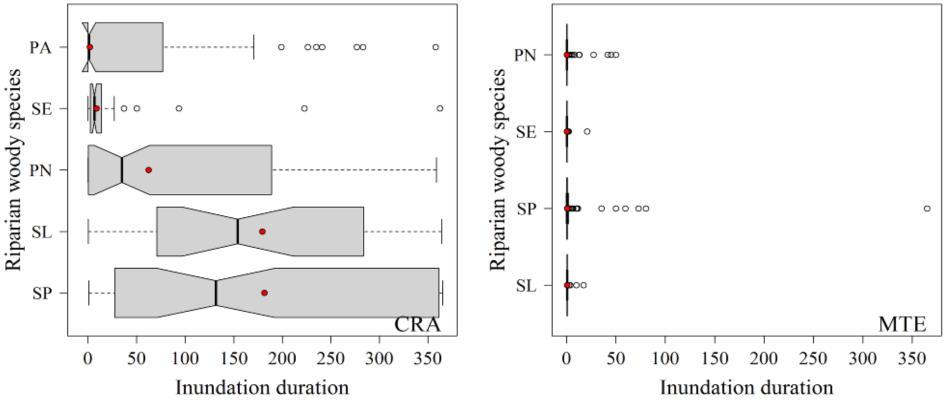


Figure 3.14. *Boxplots for the variable V1, inundation duration (Cabriel-Rabo del Batán –CRA– on the left, and Mijares-Terde –MTE– on the right). In the axis of abscissas are represented the riparian species (codes detailed in* ***Table 3.6****).*

Similarly, significant differences among species in the inundation duration during growth period (hereafter, V2) were detected at CRA ($FW_e = 28.62$; $p < 0.001$) but not at MTE (**Figure 3.15**). The multiple comparisons showed the same 3 groups of species again. Those were [SL-SP], [PN] and [PA-SE]. The species within the same group showed similar values of the Huber estimator (SL = 92; SP = 90; PN = 32; SE = 5; PA = 2). Although no differences were found at MTE, species could be divided into two groups according to their similar values of the Huber estimator (0.5 for SL and SP, and 0.3 for SE and PN).

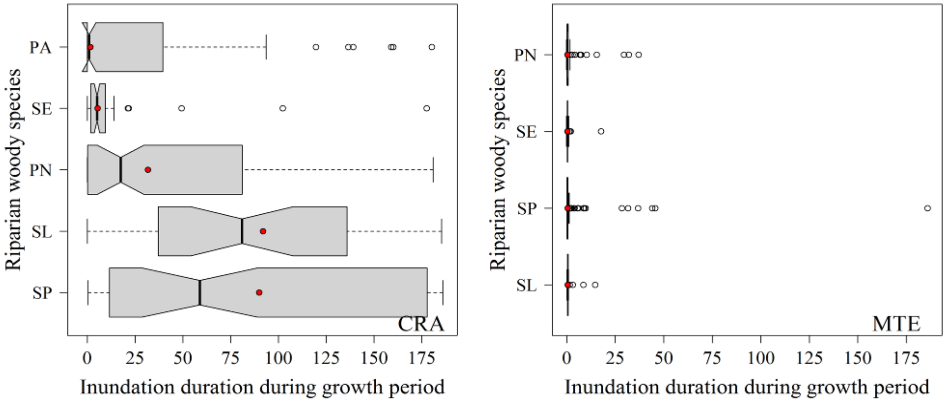


Figure 3.15. *Boxplots for the variable V2, inundation duration during growth period (Cabriel-Rabo del Batán –CRA– on the left, and Mijares-Terde –MTE– on the right). In the axis of abscissas are represented the riparian species (codes detailed in* ***Table 3.6****).*

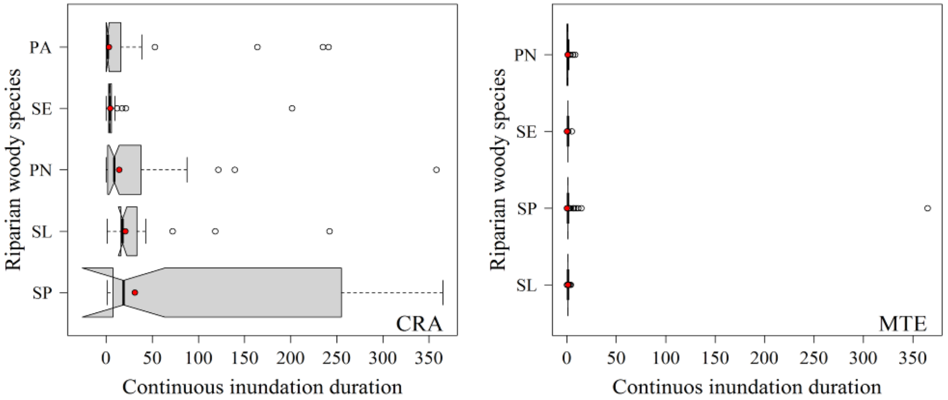


Figure 3.16. *Boxplots for the variable V3, continuous inundation duration (Cabriel-Rabo del Batán –CRA– on the left, and Mijares-Terde –MTE– on the right). In the axis of abscissas are represented the riparian species (codes detailed in* ***Table 3.6****).*

Regarding continuous inundation duration (hereafter, V3) (**Figure 3.16**), the aggregation was not as obvious as in the previous cases (higher overlap among species). Despite it, there were significant differences among some species (PA *vs.* PN, PN *vs.* SE and SE *vs.* SL) at CRA ($F_{We} = 12.20$; $p < 0.001$), but not again at MTE. The Huber estimator gave mean values quite similar to those given by the median. A coherent gradient (SP = 31, SL = 21, PN = 14, SE = 4, PA = 3) was found considering the results showed by the previous variables. Regarding MTE, the values for all species were hovering around 1 day, what suggests that the high-flow periods (even though they could be of a similar magnitude) are much shorter in MTE than CRA.

As illustrated in **Figure 3.17**, inundation frequency (hereafter, V4) showed differences among species at CRA ($F_{We} = 18.05$; $p < 0.001$), and a gradual pattern according to their Huber estimator (SL = 6, SP = 4, PN = 3, SE = 2, PA = 1 events), showing the following homogeneous groups [SL-SP], [SP-PN], [PN-SE] and [SE-PA]. Regarding MTE, no differences were found among species; in fact, they exhibited a similar value (0.4-0.5 events a year). Nevertheless, SL was the species with higher inundation frequency in both reaches.

Only in the case of elevation above base flow (hereafter, V5), we demonstrated different trimmed means for both reaches, CRA ($F_{We} = 46.16$; $p = 0$) and MTE ($F_{We} = 17.41$; $p < 0.001$). Two homogeneous groups were defined at CRA: [SL-SP] at low elevation, and [PN-SE-PA] at high elevation. Specifically, the Huber estimator showed the following values: SP = 0.02, SL = 0.06, PN = 0.55, SE = 0.63 and PA = 0.83 (m above base flow). At MTE (**Figure 3.18 right**), the groups defined were [SL] near the water, followed closely by [SP-SE] and [PN] in higher elevations. Their respective values obtained by the Huber estimator were: SL = 0.7, SP = 0.8, SE = 0.9 and PN = 1.3 (m above base flow).

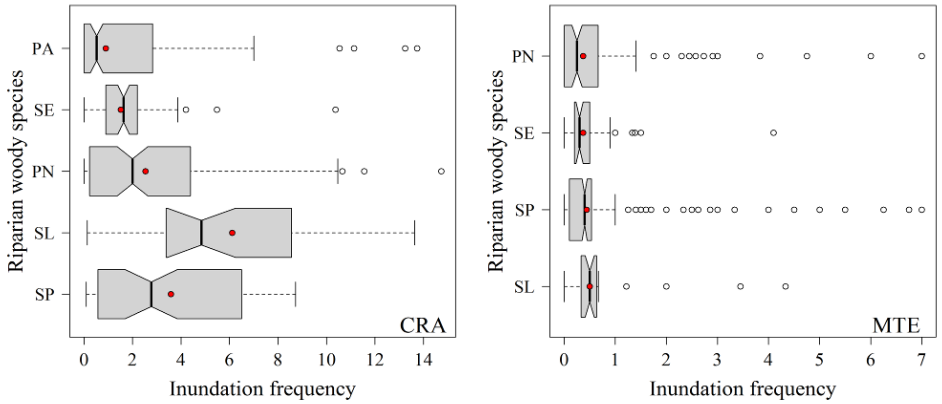


Figure 3.17. *Boxplots for the variable V4, inundation frequency (Cabriel-Rabo del Batán –CRA– on the left, and Mijares-Terde –MTE– on the right). In the axis of abscissas are represented the riparian species (codes detailed in* ***Table 3.6****).*

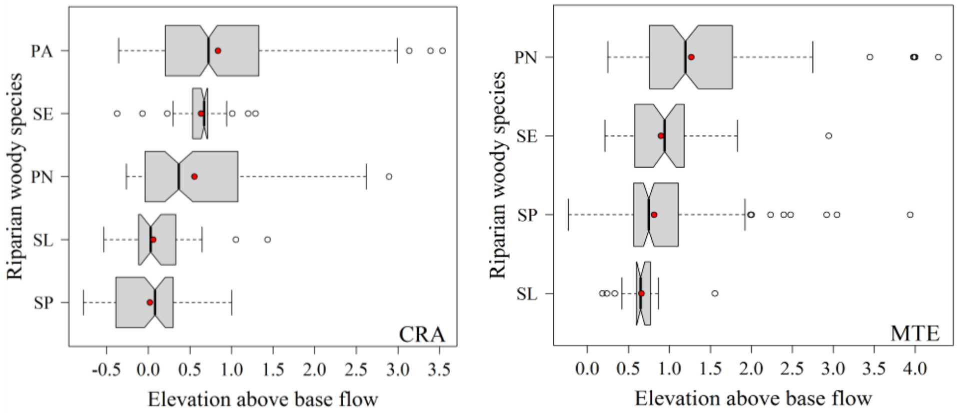


Figure 3.18. *Boxplots for the variable V5, elevation above base flow for both study sites (Cabriel-Rabo del Batán –CRA– on the left, and Mijares-Terde –MTE– on the right). In the axis of abscissas are represented the riparian species (codes detailed in* ***Table 3.6****).*

3.5.3 Curves of hydrological response

Curves of hydrological response for the species with the largest sample size (N > 75) were constructed and compared across sites, i.e. PA, PN, SE and SP in CRA and PN and SP in MTE. A histogram was used to show the distribution and frequency of each data set. Additionally, a curve was defined to envelope the data distribution of each species. The response curves in the two natural sites were not integrated into one curve due to the evident differences between sites; therefore a curve by variable and species was obtained in each site. Nevertheless, for the first four variables, the shape of the curve was quite similar among species (except some exceptions). The highest suitability was located in the first intervals of each variable.

The curve for V1 (**Figure 3.19**) highlighted the response of SP, with longer inundation compared to the rest of species in both sites. The plants were distributed almost in the entire inundation range (from 0 to 365 days per year). PN at MTE showed the shortest range, not appearing in places with inundation duration larger than 50 days per year, however, the rest of species showed their highest frequency in less than 50 days per year. For PA and PN, a second peak appeared around 150 of inundation duration. The curves showed by V2 (**Figure 3.20**) were very similar to those showed by V1. SP-CRA showed the wider range, PA-CRA and PN-CRA a smooth decreasing trend and SE-CRA, PN-MTE and SP-MTE a sharp decreasing trend.

In the case of V3 (**Figure 3.21**), SP-CRA presented longer periods of continuous inundation than the rest of species; in fact, this species was dominant in the vegetated islands inside the channel; therefore, this species could be described as the species that best withstands the continued flooding in their roots. Most of the specimens were located in the range 0-15 consecutive days per year. In terms of V4 (**Figure 3.22**), all the species showed most of their values between 0 and 1 event per year. However, species at CRA showed a relevant proportion of specimens with values higher than 1. This was more patent in SP and PN than in SE and PA. Finally, in relation to V5

(**Figure 3.23**), PA and PN obtained the larger range of variability at CRA, with some groups located higher in the banks in relation to others. SP was the species located closer to base flow, even below it. At MTE, both species presented specimens in the same range, but SP was in some cases below water level and had a higher proportion of specimens located at less than 1 m above base flow, in comparison with PN.

In the next pages, the response curves for the five hydrological variables are illustrated. In each case, the number of classes (intervals) and their specific width depends on the sample size (N) and data range.

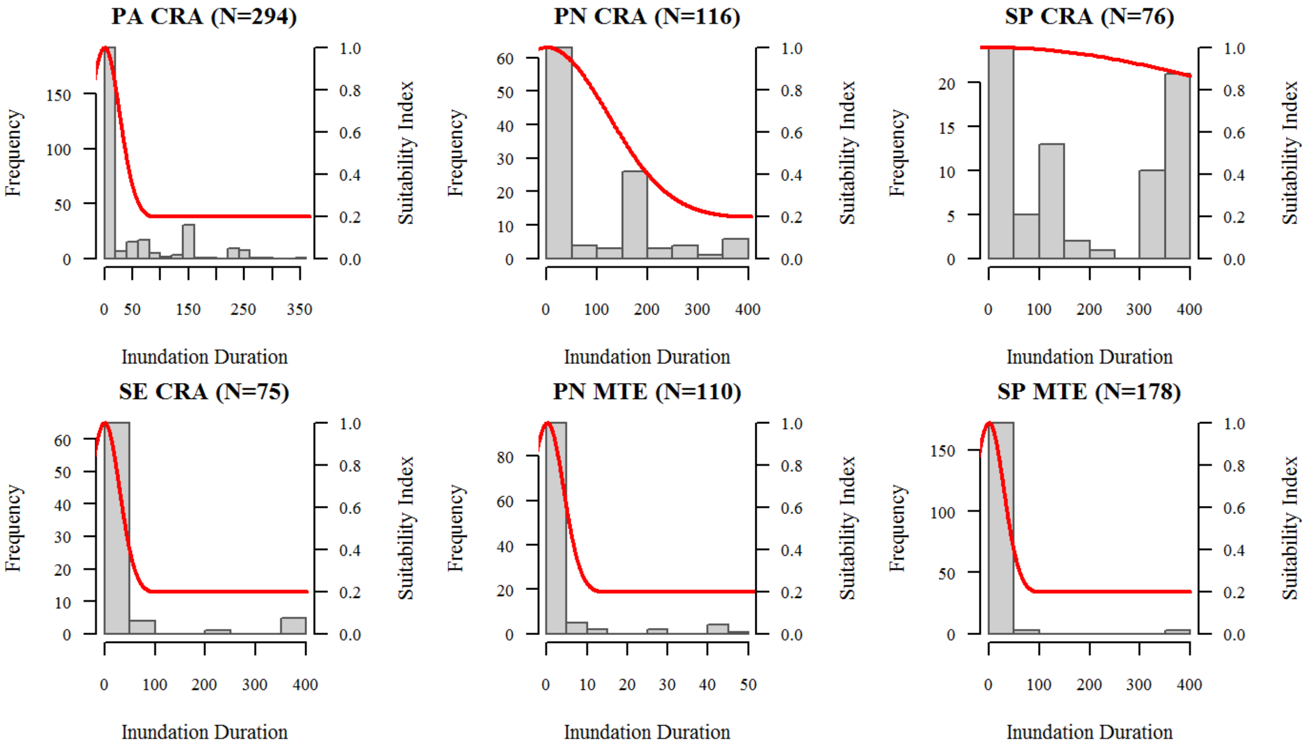


__Figure 3.19.__ Response curves of the hydrological variable V1, Inundation Duration (number of days per year), for the most abundant woody riparian species at the Cabriel-Rabo del Batán and Mijares-Terde reaches (species' codes detailed in __Table 3.6__).

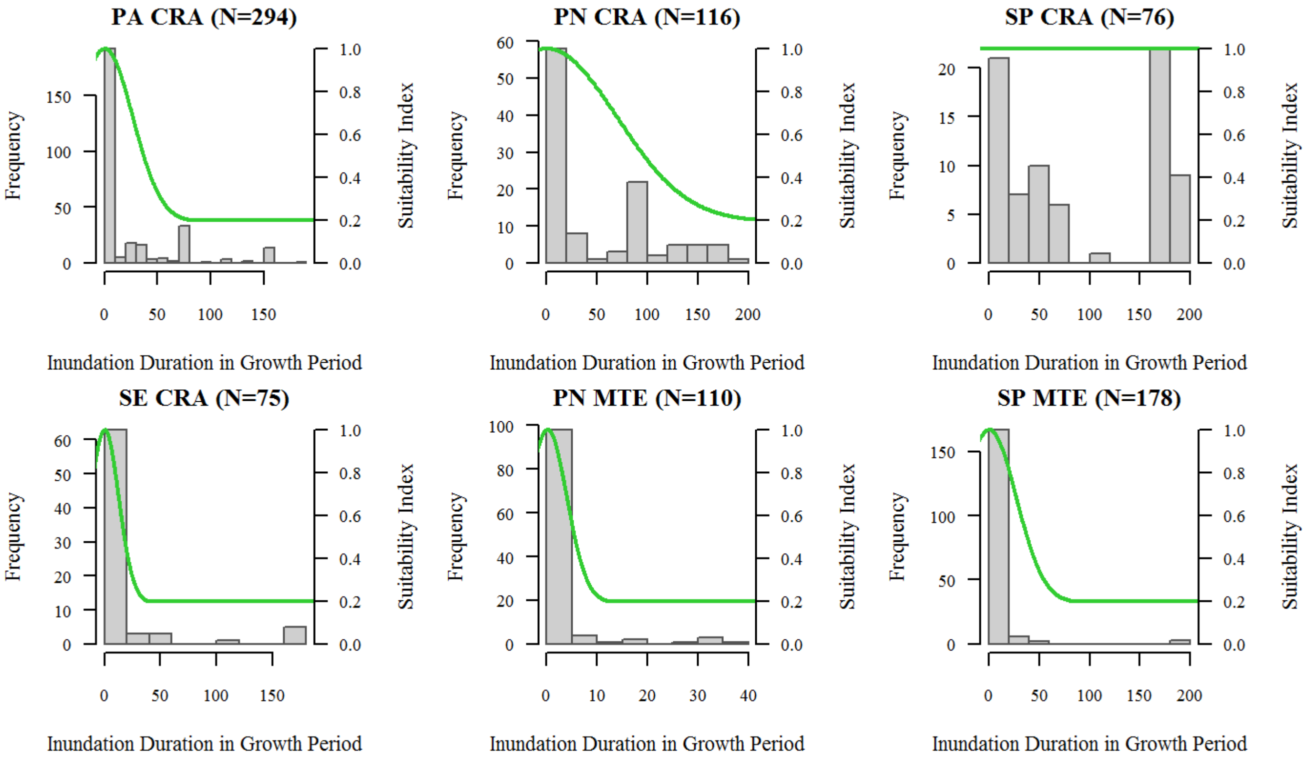


Figure 3.20. *Response curves of the hydrological variable V2, Inundation Duration (number of days per year) during Growth Period, for the most abundant woody riparian species at the Cabriel-Rabo del Batán and Mijares-Terde reaches (codes detailed in* ***Table 3.6****).*

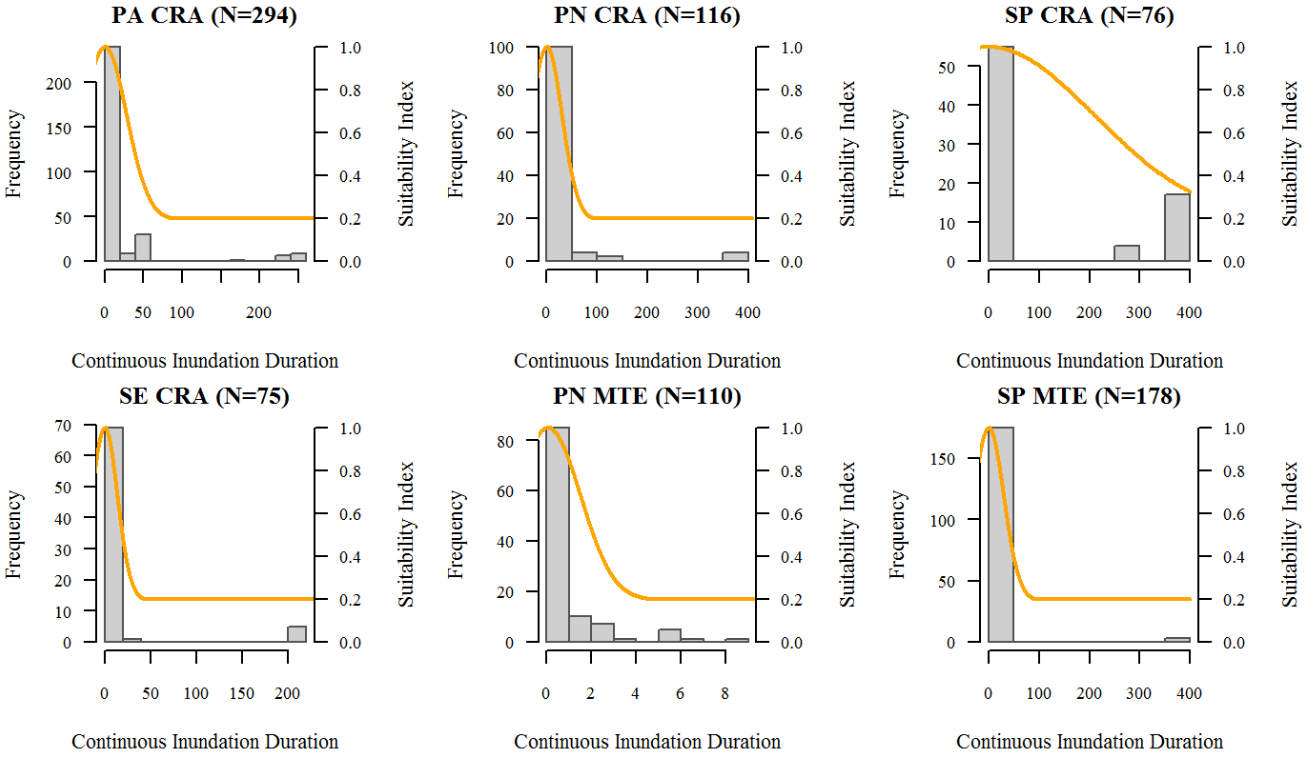


Figure 3.21. *Response curves of the hydrological variable V3, Continuous Inundation Duration (average consecutive number of days per year), for the most abundant woody riparian species at the Cabriel-Rabo del Batán and Mijares-Terde reaches (codes in **Table 3.6**).*

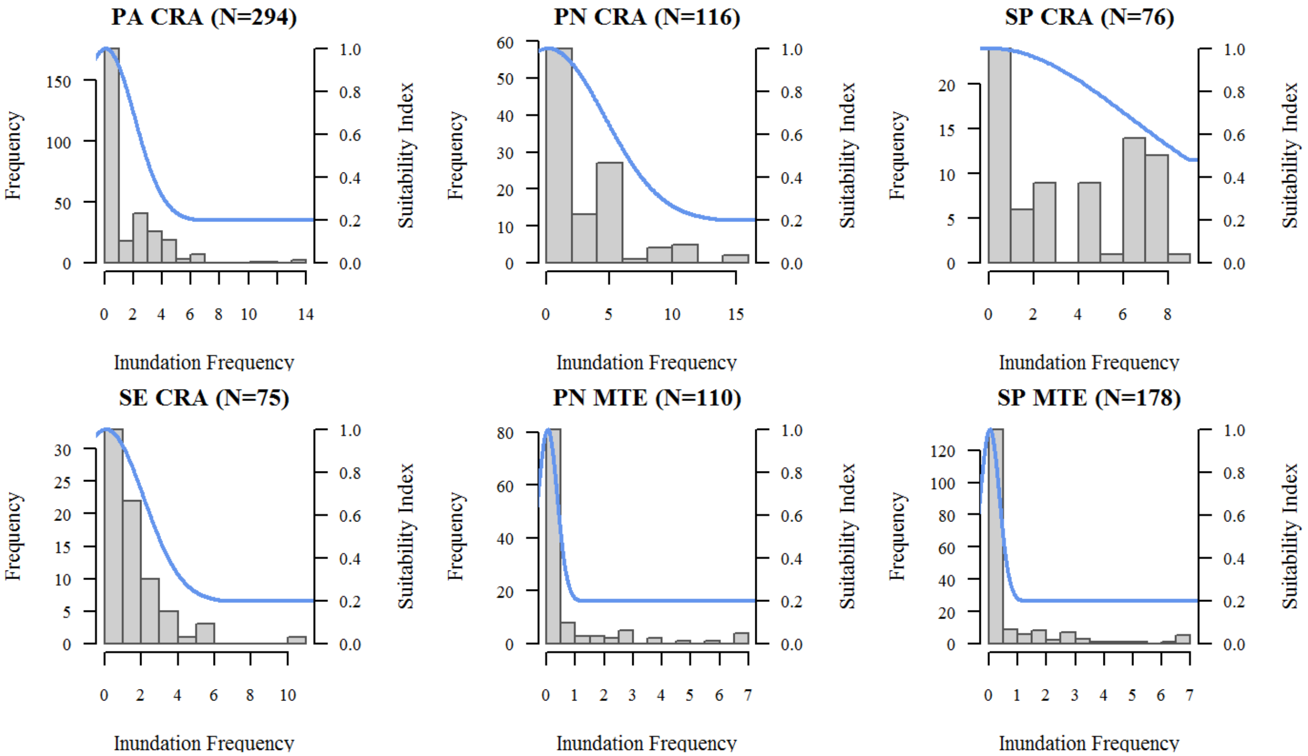


Figure 3.22. Response curves of the hydrological variable V4, Inundation Frequency, for the most abundant woody riparian species at the Cabriel-Rabo del Batán and Mijares-Terde reaches (species' codes detailed in ***Table 3.6****).*

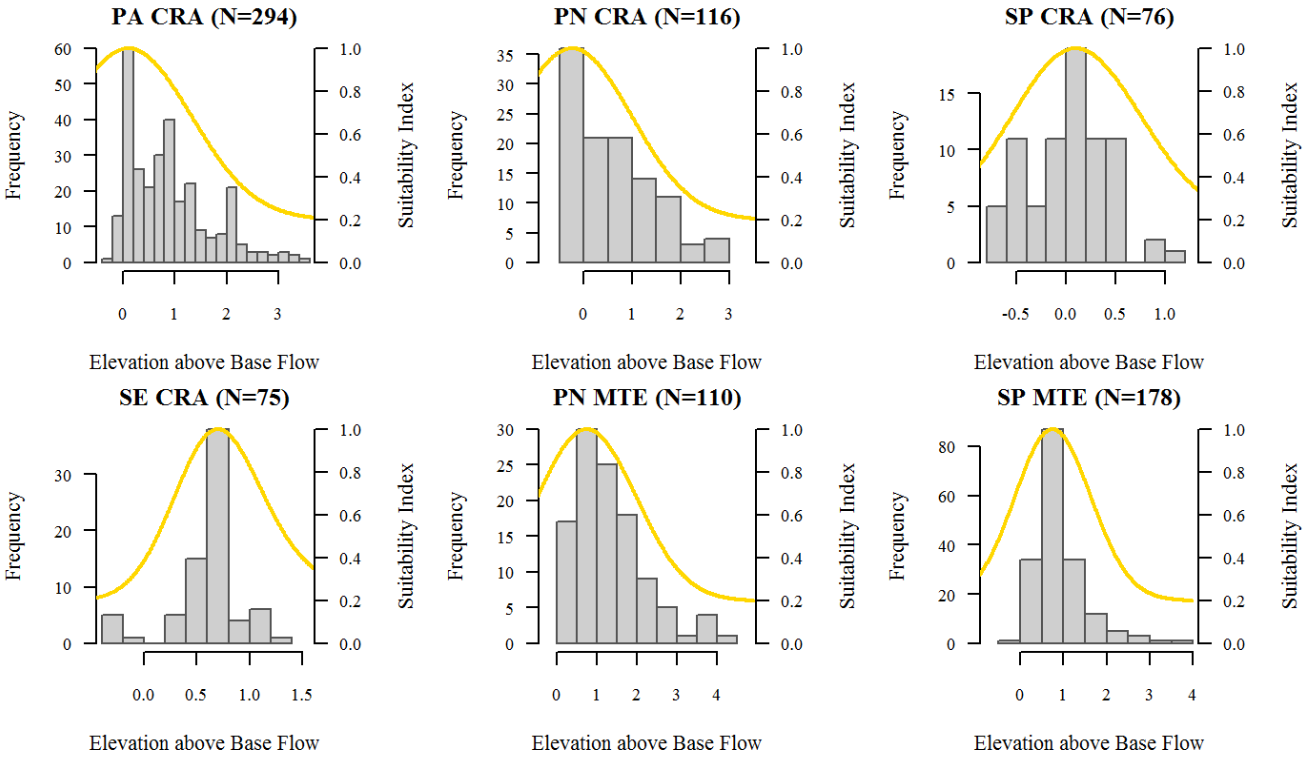


__Figure 3.23.__ Response curves of the hydrological variable V5, Plant Elevation above Base Flow, for the most abundant woody riparian species at the Cabriel-Rabo del Batán and Mijares-Terde reaches (species' codes detailed in __Table 3.6__).

3.6 DISCUSSION

3.6.1 Hydrological guilds of woody riparian species

Coupling hydraulic models with geo-referenced survey of woody riparian species, along with dendrochronological sampling, allowed us to obtain the time series of water elevations at which every single vegetation unit had been exposed during its entire lifetime. Then, through the definition of hydrological variables with ecological meaning we were able to interpret the response of those woody riparian species to flow regime and define guilds of those species.

In a first approach, we estimated that more fuzzy guilds (less clear) would be obtained using hydrological data and base flow as a reference instead of thalweg, since we were reducing the range of elevations between plants and the fixed reference, at least at the Cabriel-Rabo del Batán (CRA). On the contrary, the differences (almost null) revealed in terms of distance and elevation to/above thalweg in Mijares-Terde (MTE) could be more patent when using hydrological data.

Significant differences were found among species based on the hydrological variables at CRA, being more evident those differences in the variable elevation above base flow in the case of MTE. The presence of at least two groups or potential hydrological guilds was consistent in both river reaches. Other studies in Mediterranean rivers found significant differences among species using the elevation above thalweg (Garófano-Gómez *et al.*, 2009b), in flow-regulated sites; however, in this study we considered more species and in near-natural conditions, resulting in clearer differences.

Although the data presented some uncertainties and should be considered with caution, as it will be explained in the following section, data at CRA resulted more reliable for different reasons, and therefore, also their guilds.

Salix purpurea (SP) and *Salix alba* (SL) constituted a guild that could be defined as ‘highly tolerant to inundation’ (V1, ≥180 days; V2, ≥90 days; V3, ≥20-30 days; V4, ≥4-6 events per year; V5, ≈-0.5–0.5 m), typical of positions close to the water's edge, able to withstand the waterlooging and burial by sediments. In terms of their Wetland Indicator Status (USDA NRCS, 2012), SP is considered as *Obligate Wetland* and SL as *Facultative Wetland.* However, we did not detect such difference in our data.

In intermediate positions, we observed *Populus nigra* (PN), which is considered as *Facultative Wetland*, therefore it could be defined as 'intermediate tolerant to inundation' (V1, ≥60 days; V2, ≥30 days; V3, ≥15 days; V4, ≥3 events per year; V5, ≈ -0.5–2.0 m). Other studies, for example, those carried out by Vreugdenhil *et al.,* (2006), defined PN as a species located in the transition between softwood and hardwood forest. In the case of CRA always showed intermediate values for all the variables in comparison with the rest of the species.

Populus alba (PA) and *Salix eleagnos* (SE) would be located relatively higher from base flow level and with less inundation duration and frequency, therefore they are considered as *Facultative.* Depending on the moisture degree, SE could be considered as *Facultative Wetland* as well. Therefore, this guild could be defined as 'transitional between floodplain and terrestrial' (V1, ≥10 days; V2, ≥5 days; V3, ≥5 days; V4, ≥1-2 events per year; V5, ≈ 0-2.0 m). These results are similar to those reported by Siebel and Bouwma (1998) along the Upper Rhine in France, where PA occurs in a hardwood floodplain forest that is flooded almost every summer (June-August). Other authors have reported that PA can withstand finest soils (with relevant clay content) and warmer and drier conditions than PN because of their different root system (Ceballos and Ruiz de la Torre, 1979). This is coherent with our results, where PA occupied farther positions to water's edge more often than PN.

Crataegus monogyna (CR) was not considered for this study because of its small sample size. However, due to the position that this plant occupies (Chapter 2), it would have a response similar to PA and SE. According to the authors referred before (Vreugdenhil *et al.*, 2006), CR is better able to withstand flooding than other hardwood species. It can tolerate extreme environmental conditions, as low soil depth and high soil pH, however only very low light availability has significant negative effects on its recruitment rates (Grubb *et al.*, 1996). According to USDA NRCS (2012), CR is considered as *Facultative-Facultative Upland.*

3.6.2 Factors affecting the quality and uncertainty of response guilds and curves

Simplifications in this kind of studies are quite common (Vreugdenhil *et al.*, 2006) due to the complexity of the riparian ecosystems and the factors that drive their change (flow regime, sediment movement, etc.). In our case, certain assumptions were made to simplify the methodology, e.g. we assumed fixed river morphology and the water level at a point was assumed to be equal to the river water level. In the following paragraphs, we specify all the possible factors that could have affected the definition of guilds and response curves, covering factors such as the physical valley conditions, hydraulic model accuracy, age determination, definition of variables, etc.

Our intention was to create a response curve for each species, collecting data from different reaches belonging to a certain ecotype or strata (i.e. reaches sharing similar physical characteristics where the probability of existence and survival for a target species were similar); but we found that the sites differed in several aspects and the species showed a different response although similar guilds could be suggested by the data. It deserves to remind that both reaches are free-flowing and in nearly natural conditions, where the fluvial processes have low human affection. This was considered essential in order to find the highest natural variability in the hydrological variables analysed. Taking this into consideration, it is supposed that every species and plant should be located in the place ecologically more beneficial with respect to the available space for their establishment, although of course, not only the water availability but also other factors condition their survival after establishment, like light conditions and competence for space and nutrients, among others (Naiman *et al.*, 2005).

Although larger sample size would be needed to reduce the uncertainty of certain areas of the response curves, results showed that generalization is not possible even though both reaches were located in the headwaters of their respective basins (in relatively narrow valleys). Nevertheless, there are substantial differences between them in their flow regime (particularly in magnitude), stream order and catchment area, what can have an effect in the different response of the woody riparian species. In any case, we believe that both reaches conserve a riparian forest in good status because they are relatively narrow and in consequence, they have not been highly transformed by human uses. Probably, a study similar like this in a free-flowing lowland river section with an unrestricted development of vegetation would have came out with different results. But sadly, those ecosystems have almost disappeared. Therefore, it is not going to be possible to obtain this kind of empirical information, and expert criteria will be the only option. Whatever the case may be, an effort should be made to define the flow requirements of the riparian species in those ecosystems, since it is stated in the environmental legislation.

If the different species are distributed across the floodplain, the cross-section profile (topography) is also important. If it is heterogeneous, more differences will appear among species, but if it is homogeneous and no big differences appear between the base flow level and the elevation of the floodplain, no big differences will be found between the responses of the different species. This could be one reason explaining the small differences among species at MTE.

The flow time series were accurate and represented quite well the flow regime in our study reaches, since short distance to a gauging station of high data quality was a requirement. However, this factor could play an important role in other studies where the reaches are located far from the gauging sites. Hence, the quality of the hydrological reconstruction (considering water diversions and incomes from tributaries) is crucial (see e.g., Garófano-Gómez *et al.*, *in press*).

Another aspect is the way we have managed the river flow information. We have employed mean daily flow series transformed into a mean daily water level series. Nevertheless, numerous studies have highlighted the larger importance of the instantaneous flows (e.g. with a time step of 10 minutes) instead of the mean daily flows, as instantaneous flows can have a more direct effect in the configuration of the floodplain vegetation.

Starting from data of plants location and elevation, the determination of the flow for inundation also depends on the rating curves developed in the hydraulic model. In this step, the accuracy of the model is critical to the final step of species aggregation/grouping. However, the assessment of the roughness in heterogeneous and densely vegetated habitats is one of the factors that makes difficult to get an accurate rating curve; in any case we consider that the field survey in different water conditions (low, medium, high water level in the riparian zone) is the best option far from any assessment by 1-D or 2-D hydraulic simulation. This was the case of CRA, where we measured twice the water surface elevation (in low and high flow conditions) in all of the transects for the calibration of the model. Therefore, we consider that this model, and hence, the results obtain from this site, are more reliable.

In the assessment of hydrological variables, the use of a binomial form of inundation (yes/no) is one relevant limitation; i.e., in this study the plants were inundated when the water surface elevation was higher than the base of the plant. It means that in sites where the slope of the bank, in the cross-section, is very gentle, the plants in a wide range of the riparian zone can have a great part of their roots in the water; despite this fact, the inundation duration could be only a few days, and it depends on the rating curve developed in the hydraulic model. The fact that water table in the aquifer is considered horizontal is another limitation given the hydraulic gradient from the aquifer to the river or vice versa, and the potential effects of the capillarity fringe in diverse texture conditions. In consequence, we suggest that this empirical approach could be overpassed with the use of a gradient of inundation, e.g. the percentage of the root's elevation range that is below water table at a certain time.

Other physical factor, the slope of the banks, makes the rating curves more or less steep; therefore, in sites with more gradient, CRA site, it is more probable to find relevant differences among species. We suggest this is one of the factors that make the difference between the results in the two rivers.

The other relevant factor could be the soil texture. In soils with coarse substrate and high transmissivity, the lateral hydraulic gradient can be smaller; therefore the floodplain and banks topography (i.e. elevations) is important to evaluate and compare the access of the plants to the water. However, in soils with fine texture, where the height of the capillary fringe is very relevant, the access to water is facilitated and the effect of topography is reduced in some degree. We suggest that the interaction of these two factors, banks slope (higher in CRA) and soil texture (finer in CRA) have determined the species differences in one river and not in the other.

Although during the sampling we tried to core individuals of all sizes and hence, ages, to define a reliable growth function, for some species and sites the resultant coefficient of determination of the growth function was not high enough (e.g. case of PN). This could have had an effect in the final results. In any case, the age determination always has a certain level of uncertainty, as riparian species can present absent, faint and false rings frequently. We considered that our estimations were 1-2 years accurate, although until 5 years in dating accuracy could be considered acceptable (Ferry, 2010).

In certain situations false rings can be abundant. They represent multiple growth episodes during a single growing season, which can be caused for example by the onset of stressful conditions before the end of the growing season (Nash, 2002), or when trees are partially uprooted or the stand is eroded and the roots are situated near the surface (Buchwal, 2008). False rings also can be a consequence of flooding effects on tree-ring formation (Denneler *et al.*, 2010) and have been used to characterize temporal and spatial patterns of hydrologic connectivity or to reconstruct local patterns of seasonal drought in riparian ecosystems in semiarid regions (Morino, 2008).

Finally, the empirical results of plant observations gave interesting results, but also remark the practical difficulty of the development of hydrologic response guilds (Merritt *et al.*, 2010). Other approaches like the hydrological modelling (Francés *et al.*, 2002; Francés *et al.*, 2007) coupled with soil moisture and riparian species physiology (Morales de la Cruz and Francés, 2009; Real *et al.*, 2010; García-Arias *et al.*, *in review*) are very promising in the study of riparian functional groups and their spatial distribution, as well as the assessment of environmental flow regimes and water management scenarios for riparian conservation (Francés *et al.*, 2009; Francés *et al.*, 2011; García-Arias *et al.*, *in press*).

3.6.3 Implications for management

This study has provided valuable information on the effects of five aspects of flooding on woody riparian species, which can be applied in riparian woodland restoration projects. It has the potential of improving the design of river reforestations or plantations. Besides, riparian vegetation is nowadays an element to be considered in the assessment of environmental flow regimes, which is explicitly recognized in the Water Framework Directive (European Commission, 2000), and in the existing law and legal instruction for hydrological planning in Spain and in the River Basin Management Plans (e.g. CHJ, 1998).

The results of this study could be used to formulate practical guidelines for the selection of areas suitable for regeneration of the species considered here. The approach is then to determine in a certain study reach the thresholds of certain inundation characteristics. For example, the bands suitable for each species or guilds could be determined using a hydraulic model and a digital elevation map. Maps of every reach could be generated showing bands of different inundation duration and according to basic information of the target species (as the one developed here or by expert criteria), the most suitable areas for each species could be indicated. Therefore, this could have a direct application to the water management, considering the most suitable ranges and their associated variability in order to maintain bands with significant different values to enhance the riparian diversity.

The definition of riparian guilds may be used as a tool for assessment of the ecological integrity of rivers, for instance determining shifts in the structure of the guilds in response to river regulation (Bejarano *et al.*, 2011; Bejarano *et al.*, 2012a; Bejarano *et al.*, 2012b). Another application may be the definition of the most sensitive guilds, i.e., the group of species that share life history strategies that are highly adapted to specific riverine conditions and may decline far more than generalist species.

This information also could be useful in environmental assessment studies related to water management, like in hydropower plants, as the prolonged inundation can produce mortality of the riparian species by anoxia and salination (as a result of supersaturation of the subsoil layer). This problem has increased in the last decade with the increment in the electricity consumption in summer and therefore higher hydropower production (for example, see the case of the natural reserve of Sebes in Catalonia, website: http://www.reservanaturalsebes.org, where is taken place a high mortality of large-sized riparian specimens). Therefore, the thresholds of inundation duration should be studied in detail due to their importance for the conservation of riparian systems.

Chapter 4

Hydromorphological and floristic patterns along a regulated Mediterranean river: The Serpis River

4 ASSESSING HYDROMORPHOLOGICAL AND FLORISTIC PATTERNS ALONG A REGULATED MEDITERRANEAN RIVER: THE SERPIS RIVER

4.1 ABSTRACT

In the European context, several methodologies have been developed to assess the ecological status and, specifically, the hydromorphological status of running surface waters. Although these methodologies have been widely used, few studies have focused on hydrologically altered water bodies and the factors that may determine their status. In this study, the Serpis River was divided into 16 segments from the Beniarrés dam (40 km from the river mouth) to the sea, all of which are affected by flow regulation, but with different severity. In each segment, an inventory of the flora was conducted, and hydromorphological indices (QBR, Riparian Habitat Quality Index; and IHF, River Habitat Index) were applied. The objectives of the study were (A) to identify relationships between floristic composition and QBR components and (B) between instream habitat characteristics and IHF components as well as (C) to determine the main factors controlling the floristic composition and riparian habitat quality (QBR) and the factors controlling instream habitat characteristics and heterogeneity (IHF). A cluster analysis allowed grouping sites according to their floristic composition and instream habitat characteristics, and non-metric multidimensional scaling (NMDS) was used to ordinate the sites, obtaining the biotic and instream habitat characteristics, as well as the QBR and IHF subindices, which better explained the spatial patterns. Finally, a canonical correspondence analysis (CCA) with predictor variables (geographical, hydrological, geomorphological and human pressures) indicated the main factors controlling the spatial patterns of the floristic composition, instream habitat characteristics, riparian habitat quality and instream habitat heterogeneity. A gradient of riparian and instream habitat quality was identified. Our results suggest that physical constraints (presence of a gorge) have protected sites from severe human impacts, resulting in good ecological quality, despite hydrological alteration. This area, where there is geomorphological control, could be potentially reclassified into a different ecotype because regular monitoring could be using incorrect references for index scores, and naturally high scores could be confused with recovery from hydrological alteration or other pressures. The sites with the worst quality were near the river mouth and were characterised by an artificial and highly variable flow regime (related to large autumnal floods and frequent human-induced periods of zero flow). This artificial flow variability as well as the presence of lateral structures in the river channel and geomorphological characteristics were identified as the main factors driving the hydromorphological and floristic pattern in this regulated river.

Keywords: Hydromorphological indices, ecological status, floristic composition, ecotypes, Júcar River Basin, environmental flows, Mediterranean rivers.

4.2 INTRODUCTION

The flow regimes of Mediterranean streams exhibit strong seasonal and annual variability (Blondel and Aronson, 1999; Gasith and Resh, 1999). This variability has been one of the main motivations for the construction of dams in regions with a Mediterranean climate, such as Spain, where there are approximately 1200 large dams (World Commission on Dams, 2000; Kondolf and Batalla, 2005). These hydraulic structures provide many services to society, e.g., flood control, power generation and supplying water for irrigation, drinking water, industrial use and recreation; however, they also modify basic components of the flow regime. These alterations have produced many hydromorphological and biotic changes in Mediterranean river ecosystems. Moreover, flow regimes are associated with biological and physical thresholds that determine river dynamics, and thus the presence of different flora and fauna communities (Poff *et al.*, 1997). This flow-biota interaction is especially remarkable in Mediterranean rivers (Prenda *et al.*, 2006) due to their high biological diversity and extremely variable flow regimes (Blondel and Aronson, 1999; Naiman *et al.*, 2008).

Hydraulic structures, such as dams, not only disrupt the longitudinal continuity of the flow within a river, but also act as barriers to sediments, fish migration and vegetation propagules (Brierley and Fryirs, 2005; Charlton, 2008). In addition, they induce changes in the thermal regime, water quality and biogeochemical fluxes, impacting habitat availability and connectivity along the fluvial continuum (Van Steeter and Pitlick, 1998; Brierley and Fryirs, 2005; Garde, 2006). Lateral connectivity is also altered by the reduction of the frequency, magnitude and duration of events that periodically flood banks and floodplains (Charlton, 2008), causing loss of native riparian vegetation (Burch *et al.*, 1987). Many native species of riparian vegetation exhibit life cycles adapted to seasonal peak flows, the loss of which may hinder the regeneration of these riparian communities, reducing their growth rates or favouring the invasion of alien species (Poff *et al.*, 1997).

Integrity of the hydrogeomorphological processes in rivers is crucial to ensure the complexity and heterogeneity of fluvial ecosystems (Poff *et al.*, 1997; Brierley and Fryirs, 2005). For this reason, assessment of hydromorphological characteristics within fluvial ecosystems has been established as a component in evaluating the ecological status of rivers in Europe (i.e., the Water Framework Directive: WFD; European Commission, 2000), and worldwide (e.g., the Clean Water Act in North America; US Government, 1977). The hydromorphological quality elements to be addressed in these evaluations (listed in Annex V of the WFD) are the hydrological regime (characterised by the quantity and dynamics of water flows and connection to groundwater bodies), river continuity and morphological conditions (characterised by river depth and width variation, the structure and substrate of the riverbed and the structure of the riparian zone). According to these criteria, several researchers have developed methods to monitor the effects of hydromorphological pressures on rivers with respect to floodplain, riparian, bank and channel characteristics (Fernández *et al.*, 2011).

On the Iberian Peninsula, regarding the assessment of riparian characteristics, Munné *et al.* (1998) proposed the Riparian Habitat Quality Index (QBR, from its original name *Qualitat del Bosc de Ribera*) to assess the ecological quality of riparian habitats in rivers and streams, while Gutiérrez *et al.* (2001) developed the River Vegetation Index (IVF, from *Índex de Vegetació Fluvial*), which integrates floristic information and evaluates the conservation status of riparian zones using riparian vegetation as a bioindicator (ACA, 2008); the latter index requires more detailed knowledge of flora than other indices. Moreover, using a more functional approach, the Riparian Quality Index (RQI) proposed by González del Tánago *et al.* (2006) considers the structure and dynamics of riparian zones in a hydrological and geomorphological context, in contrast to other methods, which focus almost exclusively on assessing the current state of vegetation cover (González del Tánago *et al.*, 2006). Magdaleno *et al.* (2010) proposed the Riparian Forest Evaluation (RFV) to assess the ecological condition of riparian forests in perennial rivers. RFV has also been designed to be calculated with LIDAR data, which represents an advance compared to the aforementioned indices, as it can be calculated for larger areas.

With respect to the assessment of instream channel characteristics, the River Habitat Index (IHF, from its original name *Índice de Hábitat Fluvial*) evaluates relationships between habitat heterogeneity and physical variables related to the stream channel, which are influenced by hydrology and substrate composition (Pardo *et al.*, 2004). However, it does not assess hydromorphological features themselves but instead evaluates their quality for associated aquatic communities (Ollero Ojeda *et al.*, 2008). Quite recently, Ollero *et al.* (2008) created the Index for Hydro-Geomorphological assessment (IHG, from its original name *Índice Hidrogeomorfológico*), in which the main focus is on the protection of hydrogeomorphological dynamics, as they are an essential issue for river conservation; this index considers the functional quality of fluvial systems, channel quality and the quality of river banks (Ollero Ojeda *et al.*, 2009; Ollero *et al.*, 2011).

Although all these indices are currently in use, few studies have focused on their performance in hydrologically altered water bodies. Moreover, the indices' ability to reflect the correspondence between hydrological alteration and hydromorphological status in regulated river systems has not been properly tested. Thus, in the present study, we were interested in investigating the response of riparian flora and certain instream habitat characteristics in an altered river ecosystem as well as of the QBR and IHF indices, which are the most widely used indices by Spanish water administrations (Aguilella *et al.*, 2005; ACA, 2006).

The objectives of this study were:

A. To identify relationships between floristic composition and QBR values at sites in a hydromorphologically altered river;

B. To identify relationships between instream characteristics and IHF values at the same altered sites; and

C. To determine the main factors controlling the floristic composition and riparian habitat quality (QBR), instream habitat characteristics and instream habitat heterogeneity (IHF) at these sites.

4.3 METHODS

4.3.1 Study area

The source of the Serpis River is situated 1462 m above sea level and is surrounded by two natural parks (Carrascar de la Font Roja and Serra Mariola). Its basin (752.8 km^2) is included in two provinces, Alicante (headwaters and middle course) and Valencia (East of Spain), within the domain of the Júcar River Basin District (**Figure 4.1**). The river runs 74.5 km from SW to NE to reach the Mediterranean Sea. It is intermittent in the initial part of its upper basin, but soon thereafter it exhibits a regular course following the confluence with the Valleseta, Penàguila, Barchell and Polop Streams. The main tributaries in the middle course are the Barranco de l'Encantada and the Agres Stream; and finally, the Bernisa River in the lower course.

The main climate type in the basin is coastal Mediterranean (Pérez, 1994), with an average annual temperature of 16.3 ºC and average annual precipitation of 630 mm (Viñals *et al.*, 2001). With respect to its lithology and geology, the Serpis river basin rises from the tip of the Betic mountain range at its Mediterranean coastal extreme. The upper basin, near Alcoy (Alicante), runs across marl deposits. The only large dam is found in the middle course (Beniarrés), associated with geology consisting of limestone and marls. From Lorcha (8 km downstream of the dam), the river becomes narrower as it flows through the limestone gorge known as *Barranco del Infierno*, which ends near Villalonga. After this town, the valley widens and the floodplain is covered by irrigated farmland, smallholdings and a high proportion of citrus orchards. The mouth of the river is located on alluvial quaternary deposits in the coastal plain known as *Plana de Gandía-Denia*. Although remarkable morphological differences are observed within the river, its entire course has been classified into one ecological typology: *mineralised river in middle and low Mediterranean mountain*, coded as ecotype 9 (CEDEX, 2004).

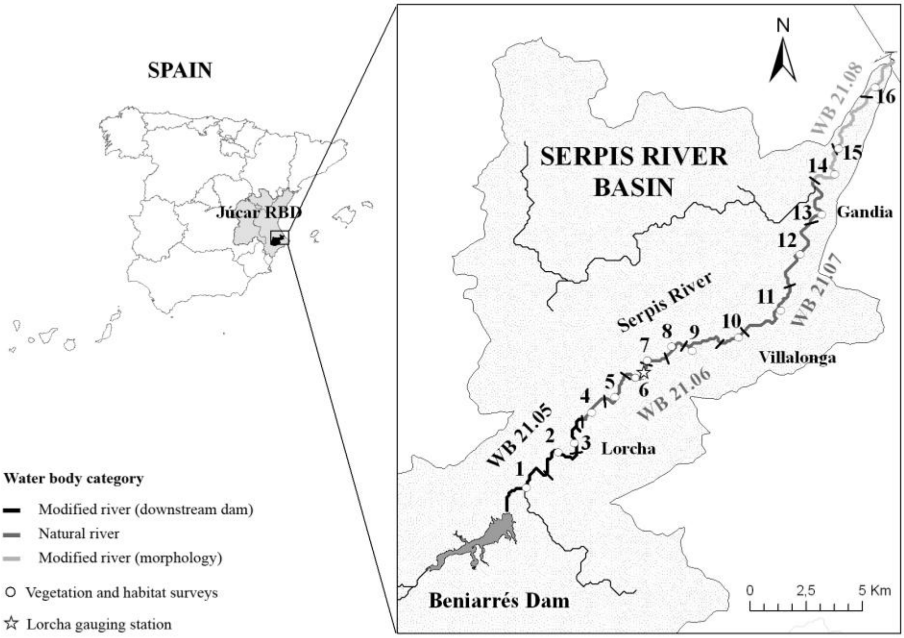


Figure 4.1. *Location of the 16 study sites and segments in the river Serpis downstream of Beniarrés dam in the Júcar River Basin District (RBD), East Spain. Water body categories follow the classification of the Júcar River Basin Authority.*

The study area consists of the territory from the Beniarrés dam to the river mouth, where four water bodies have been distinguished within this area (**Figure 4.1**) by the Júcar River Basin Authority (CHJ, 2005a; CHJ, 2009b). According to the WFD (article 2.10), a water body is a discrete and significant element of surface water, such as a river, lake or reservoir, or a distinct volume of groundwater within an aquifer. Water bodies exhibit homogeneous characteristics in their extension and length and can be separated from other water bodies due to the presence of artificial barriers (e.g., weirs or reservoirs) or natural hydromorphological changes, such as the confluence of two rivers or the presence of protected areas. According to article 2 of the WFD, a water body can be identified as *heavily modified* (HMWB) by a European Member State (in accordance with the provisions of Annex II) if human activity has substantially changed its nature (hydromorphological characteristics), and it is not possible to achieve a good ecological status. This is the case for the first water body below the dam (code 21.05) because its flow regime is substantially altered by the dam. The second and third water bodies (codes 21.06 and 21.07), which are located in the gorge, have been classified as *natural* by the Water Authority, despite presenting an impaired flow regime. Finally, the fourth water body (code 21.08) has also been classified as an HMWB, mainly due to severe changes in its original morphology (almost the whole river course is channelized).

The large Beniarrés dam, located 40 km upstream of the river mouth, has altered the hydrological regime of the Serpis River to supply irrigation water since its construction in 1958. According to the CHJ (2007), water abstraction from surface water bodies is mainly carried out for the purpose of irrigation because urban areas are supplied from wells. The main irrigation channels in the basin in terms of the volume of water abstracted are *Canales Altos del Serpis* (located in site 8) and *Acequia Real de Gandía* (in site 11). These two channels supply 81.2 % of the total demand of surface water, which is considered to represent high abstraction pressure on the river. In addition to these hydrological modifications, the Serpis River is associated with important point and diffuse pollution sources due to certain land uses and fires, respectively, and the most substantial morphological changes in the river are related to structures for water regulation and abstraction as well as the canalisation of its final reach (CHJ, 2005a).

4.3.2 Geographical characterisation

To explore the characteristics of this river, the 4 water bodies were divided into 16 homogeneous segments based on several previous visits to the area and aerial photographs of the catchment. Differences in valley form, riparian vegetation composition, the presence of artificial structures and discontinuities in adjacent land uses were also taken into account in the segmentation process. **Figure 4.2** shows the general view of two points belonging to different water bodies where differences in all the aforementioned factors can be appreciated.

The first water body immediately downstream of the dam included 3 segments; 10 segments were located in the two following water bodies; and the last 3 segments were situated in the most downstream water body (**Table 4.1**). In each segment, a representative study site of 100 m in length was selected to calculate index scores and to carry out vegetation inventories. For a full description of the sites, see Garófano-Gómez *et al.* (2009a).

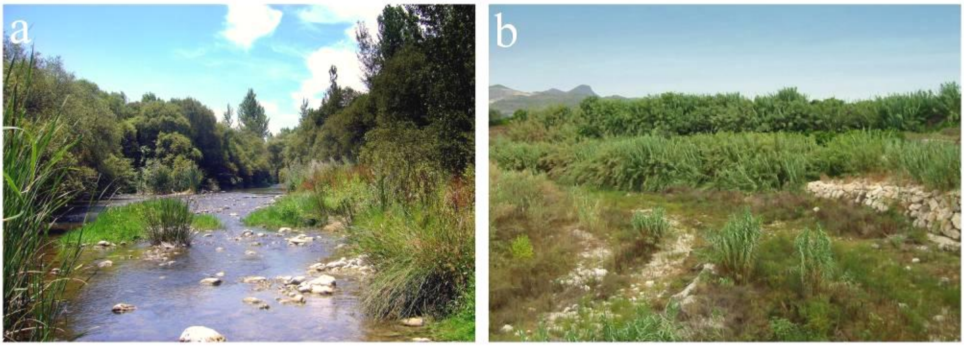


Figure 4.2. *General views of two points in the Serpis River Serpis downstream of Beniarrés dam. Photograph a taken in the first water body (code 21.05) and photograph b taken in the third water body (code 21.07).*

Elevation (Elev; in m above sea level) and distance to the nearest weir upstream (DistWeir; km) were determined at the central point of each site. Segment length (Length; km), distance from the Beniarrés dam (DistRese; km), mean slope (SlopeReach; %), accumulated watershed area (Area; km^2) below the dam (upstream of the dam discounted) and watershed mean gradient (SlopeArea; %) were determined for each river segment. These characteristics were calculated from 1:10 000 scale maps using Archydro extensions created by the Center for Research in Water Resources (University of Texas-Austin, 2003) for ArcGIS^{TM} 9.3.1 software of ESRI (Redlands, California, 2009).

Table 4.1. *Environmental characteristics of the 4 water bodies studied in the Serpis River, East Spain (X: mean value, R: range, SD: standard deviation). Variable codes are explained in the text (methods section).*

WB code*	**21.05**			**21.06**			**21.07**			**21.08**		
WB name	**Beniarrés Dam - Lorcha**			**Lorcha - Reprimala**			**Reprimala - La Murta**			**La Murta – Sea**		
Segments	1, 2, 3			4, 5, 6, 7, 8, 9			10, 11, 12, 13			14, 15, 16		
Total length (km)	8.07			10.22			10.43			8.17		
	X	R	SD	X	R	SD	X	R	SD	X	R	SD
Elev (masl)	257.2	(243.0-273.0)	15.1	184.3	(134.0-229.0)	35.5	61.3	(32.5-94.5)	27	10	(3.5-15.0)	5.9
Length (km)	2.7	(1.8-3.6)	0.9	1.8	(1.3-2.3)	0.4	3.1	(1.3-4.2)	1.3	2.6	(2.0-3.2)	0.6
DistRese (km)	4.6	(1.8-6.9)	2.6	13.2	(9.0-16.9)	2.9	24.3	(19.7-28.8)	4	34.8	(32.6-37.8)	2.7
Area (km^2)	33.5	(7.7-49.8)	22.5	80.5	(71.9-90.8)	7.4	114.5	(97.3-132.9)	15.9	304	(289.1-331.2)	23.6
SlopeArea (%)	25	(22.1-26.7)	2.5	30.4	(28.0-32.5)	1.7	32.5	(30.3-34.0)	1.7	26.6	(26.4-26.9)	0.3
SlopeReach (%)	0.6	(0.5-0.7)	0.1	1.3	(0.8-2.1)	0.5	0.6	(0.5-0.7)	0.1	0.2	(0.2-0.3)	0.1
DistWeir (km)	4.7	(1.9-6.9)	2.5	4.3	(0.8-10.7)	4.3	2.5	(1.4-4.9)	1.6	10.9	(8.7-13.9)	2.7
Fmin (m^3/s)	0.2	(0.2-0.2)	0	0.1	(0.0-0.2)	0.1	0	(0.0-0.0)	0	0	(0.0-0.0)	0
Fmean (m^3/s)	1.1	(1.1-1.1)	0	1	(0.7-1.1)	0.1	0.7	(0.6-0.7)	0.1	0.9	(0.9-1.0)	0
Fmax (m^3/s)	14.5	(14.5-14.5)	0	14.5	(14.5-14.7)	0.1	15.5	(14.7-16.3)	0.7	22.6	(22.5-22.9)	0.2
Fper10	0.4	(0.4-0.4)	0	0.3	(0.0-0.4)	0.2	0	(0.0-0.1)	0	0	(0.0-0.0)	0
Fper95	2.1	(2.1-2.1)	0	2.1	(2.0-2.1)	0	2.1	(2.0-2.2)	0.1	2.9	(2.9-3.0)	0
Fsd	1.5	(1.5-1.5)	0	1.5	(1.5-1.5)	0	1.6	(1.5-1.7)	0.1	2.4	(2.4-2.4)	0
Fcv	1.4	(1.4-1.4)	0	1.5	(1.4-2.1)	0.3	2.5	(2.1-2.8)	0.4	2.5	(2.5-2.5)	0

* According to Júcar River Basin Authority

Table 4.2. *Biotic characteristics of the 4 water bodies studied in the Serpis River, East Spain (X: mean value, R: range, SD: standard deviation). Variable codes are explained in the text (methods section).*

WB code	**21.05**			**21.06**			**21.07**			**21.08**		
WB name	**Beniarrés Dam - Lorcha**			**Lorcha - Reprimala**			**Reprimala - La Murta**			**La Murta - Sea**		
Segments	1, 2, 3			4, 5, 6, 7, 8, 9			10, 11, 12, 13			14, 15, 16		
	X	R	SD	X	R	SD	X	R	SD	X	R	SD
AnnualH	4	(2-7)	3	6	(3-8)	2	6	(3-9)	3	4	(3-5)	1
PerennH	27	(24-31)	4	26	(21-32)	4	23	(17-31)	6	12	(11-12)	1
Shrubs	8	(6-10)	2	9	(5-13)	3	6	(5-9)	2	6	(3-7)	2
Trees	4	(3-6)	2	4	(3-5)	1	5	(0-7)	3	2	(1-3)	1
Ferns	0	(0-1)	1	1	(0-1)	1	1	(0-1)	1	0	(0-0)	0
Hydroph	7	(5-10)	3	7	(5-8)	1	6	(3-8)	2	2	(2-2)	0
Natives	39	(24-47)	7	40	(27-47)	7	31	(19-43)	10	15	(14-16)	1
Exotics	5	(3-8)	3	5	(4-6)	1	9	(6-11)	2	8	(6-10)	2
Richness	44	(38-55)	10	46	(33-52)	7	40	(25-54)	12	23	(21-25)	2
P.AnnualH	7.7	(5.1-12.7)	4.3	12	(9.1-18.6)	3.6	14.2	(9.1-18.9)	4.4	18.8	(12.5-23.8)	5.8
P.PerennH	63	(56.4-71.1)	7.5	58	(50.0-63.6)	5.2	57.9	(52.3-68.0)	7	50.3	(45.8-57.1)	6
P.Shrubs	19	(15.8-23.1)	3.7	20	(15.2-25.0)	3.9	16.3	(11.1-20.5)	4.7	23.8	(14.3-29.2)	8.3
P.Trees	9.7	(7-9-10.9)	1.6	9	(5.8-12.1)	2.6	10.6	(0-15.9)	7.2	7.1	(4.0-12.5)	4.7
P.Ferns	0.6	(0.0-1.8)	1	1	(0.0-2.2)	1.1	1	(0.0-2.3)	1.2	0	(0.0-0.0)	0
P.Hydroph	16.5	(12.8-18.4)	3.2	14.7	(9.6-21.2)	4.1	13.6	(11.4-16.2)	2.3	8.6	(8.0-9.5)	0.8
P.Natives	88.2	(85.5-92.1)	3.5	87.9	(81.8-91.3)	3.5	76.5	(73.0-79.6)	2.8	64.6	(58.3-71.4)	6.6
P.Exotics	11.8	(7.9-14.5)	3.5	12.1	(8.7-18.2)	3.5	23.5	(20.4-27.0)	2.8	35.4	(28.6-41.7)	6.6

4.3.3 Biological data collection

A rectangular plot of 400 m^2 was the sampling area for conducting flora inventories at each site (**Figure 4.3**). Inventories were carried out during the dry season (August 2006). Plant species were recorded and the overhead percentage cover was estimated visually using the modified Braun-Blanquet cover-abundance scale (Mueller-Dombois and Ellenberg, 1974) as follows: + (a few scattered specimens, canopy cover $\leq$1 %), 1 (1-10 %), 2 (11-25 %), 3 (26-50 %), 4 (51-75 %), 5 (76-100 %). Species not identified in the field were collected and identified in an herbarium. To analyse the floristic data, the ranks were transformed to the mean percentage cover of each class (1, 5, 17.5, 37.5, 62.5 and 87.5), which is a common transformation of cover to abundance in phytosociology (van der Maarel, 1979; Wildi, 2010).

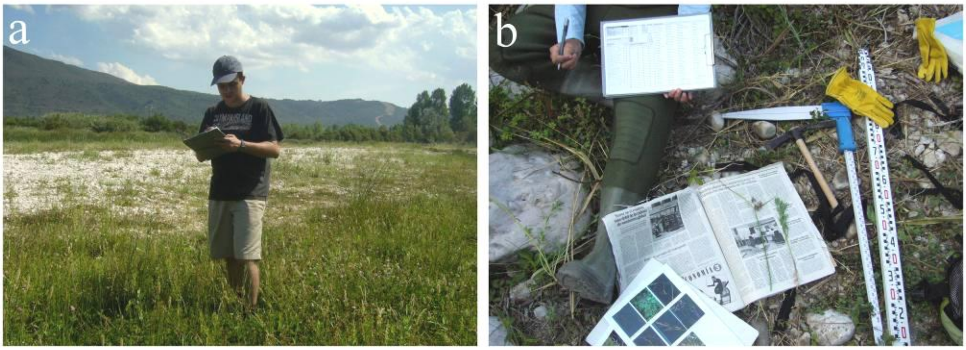


Figure 4.3. *Conducting flora inventories in the Serpis River during the field campaign (a) and keeping specimens some plants in the press to be identified in the herbarium (b).*

Seventeen variables were obtained from the floristic data (**Table 4.2**): total richness (Richness), richness of annual herbs (AnnualH), perennial herbs (PerennH), shrubs (Shrubs), trees (Trees), ferns (Ferns) and hydrophytes (Hydroph), richness of native (Natives) and exotic species (Exotics) and the abundance percentages of the aforementioned groups (P.AnnualH, P.PerennH, P.Shrubs, P.Trees, P.Ferns, P.Hydroph, P.Natives, P.Exotics).

4.3.4 Hydromorphological characterisation

The medians of the mean daily flows by months were calculated for two time periods: (a) 1943-1953, i.e., the natural flows before dam construction; and (b) 1999-2009, i.e., the regulated flow regime, using data from the gauging station at Lorcha (located at site 6) to illustrate the change in the hydrological pattern before and after regulation (**Figure 4.4**).

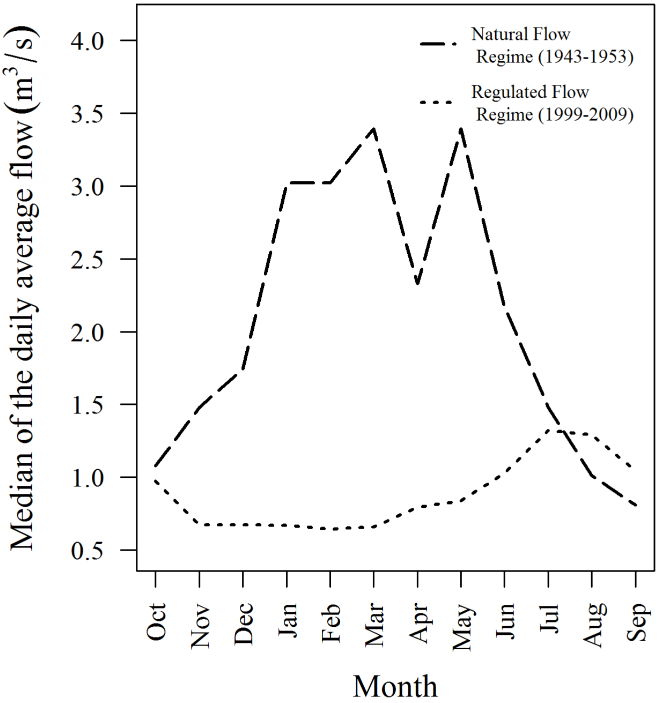


Figure 4.4. *Medians of the mean daily flow by month in the gauging station at Lorcha (downstream of the Beniarrés dam) under natural conditions (1943-1953) and after dam construction (1999-2009).*

The hydrological regime for sites 1 to 8 was characterised using average monthly flow data available from the same gauging station for the period 1999-2006. The discharge, drainage area and the two main water abstractions were used to estimate the discharge at the ungauged sites downstream of the Lorcha gauging station following the guidelines of Caissie and El-Jabi (1995) and Caissie (2006). Seven hydrological variables were obtained in each river segment: the minimum (Fmin), mean (Fmean) and maximum flow (Fmax), 10th and 95th percentiles (Fper10 and Fper95, respectively), standard deviation (Fsd) and coefficient of variation (Fcv) of the mean monthly flows (**Table 4.1**).

The mean (Dmean) and maximum river depth (Dmax) were estimated at 3 points along 5 transects at equal distances, while water surface width (Wwid) was estimated from the average of the 5 transects. Nine substrate types were considered in the margins and floodplain (R: bedrock, BB: big boulders, B: boulders, CB: cobbles, GR: gravel, FG: fine gravel, SA: sand, SI: silt and CL: clay) following a simplified classification of the American Geophysical Union (Martínez-Capel, 2000), and their percentage surface coverage was estimated visually. The percentage area associated with different water surface patterns was estimated using 4 classes: NoFlow, Flow1 (slow flow, mainly pools), Flow2 (medium, currents and glides) and Flow3 (fast, runs and riffles). Other variables recorded were the stability of the river bed and shading. Stability, i.e., the percentage of riverbed areas with a different mobility, was divided into 4 classes: Stab1-solid/hard (mainly bedrock and big boulders, an increase in the flow does not cause obvious erosion), Stab2-stable (mainly gravel and cobbles, substrate little disturbed by an increase in the flow), Stab3-instable (fine gravel and sand, particles easily transported by an increase in flow) and Stab4-soft (areas covered with silt). Shading was estimated as the percentage cover of different shade types over the channel in 3 classes: NoShade, Shade1-moderate and Shade2-dense (>70 %).

Two indices were used to determine the spatial variation of the hydromorphological status of the river and its banks: QBR and IHF. The riparian habitat quality index (QBR; Munné *et al.*, 2003) evaluates four components or subindices: total riparian vegetation cover (QBR1), vegetation cover structure (QBR2), vegetation cover quality (QBR3) and river channel alterations (QBR4). Two additional components of this index were considered:

total geomorphological score (Stype) and geomorphological type of riparian habitat (Tgeo). According to Munné *et al.* (2003), the geomorphological score establishes three types of riparian habitats depending on the form and slope of the riparian environment and the presence of islands and hard substrata. Type 1 is related to closed riparian habitats (typical of headwaters), type 2 to midland riparian habitats (large gallery forests, middle reaches) and type 3 to large riparian habitats (lower courses). The total QBR score is the sum of the scores for the 4 items and varies between 0 and 100 points, classifying riparian quality into class I ($QBR \geq 95$), of excellent quality; class II ($90 > QBR > 75$), of good quality; class III ($70 > QBR > 55$), of moderate quality (beginning of important alteration); class IV ($50 > QBR > 30$), of poor quality (important alteration); and class V ($QBR \leq 25$), of bad quality (extreme degradation).

The river habitat index (IHF; Pardo *et al.*, 2004) is the sum of 7 subindices, coded as follows: riffle embeddedness or sedimentation in pools (IHF1), riffle frequency (IHF2), substrate composition (IHF3), flow velocity/depth regime (IHF4), shading of stream bed (IHF5), elements of heterogeneity (IHF6), e.g., roots, leaves and wood, and aquatic vegetation cover (IHF7). The total IHF score fluctuates between 0 and 100 points and is not classified into categories; a higher value indicates greater habitat diversity. However, IHF scores need to be adapted to each river typology because habitat heterogeneity may vary with river type. In general, a habitat with an IHF below 40 is considered to be affecting the associated biological communities (Prat *et al.*, 2009). In this study, the IHF was classified into three classes: I ($IHF > 60$), good habitat quality; II (IHF 40-60), moderate quality, indicating that the habitat is sensitive to degradation; and III ($IHF < 40$), bad quality, indicating that the habitat is impoverished and can limit the presence of certain species, following previous studies of Mediterranean rivers (Vila-Escalé *et al.*, 2005).

4.3.5 Human impacts and pressures

Finally, six variables related to human impacts and pressures were assessed at the sites using a ranking of magnitude. These variables were considered as *absent* when they were not identified at the site; as *present* when they were identified at one or a few points of the site, but scattered around the area; and as *extensive* when they were identified throughout the entire site or at multiple points. The variables assessed following these criteria were the presence of rigid lateral structures along margins (Struct), such as channelization, embankments or lateral protections, edifications in the floodplain (Urban), rubbish and rubble (Rubble), the influence of weirs (Weirinf) and land use at margins (Agric-agricultural and Vfor-forest vegetation).

4.3.6 Variable classification

Before the statistical analyses, all of the variables were classified into predictor and response variables. The predictor variables were the subindices Stype and Tgeo (these are geomorphological variables not related to pressures) and the geographical (Elev, SlopeReach, SlopeArea and Area) and hydrological variables (Fmin, Fmean, Fmax, Fper10, Fper95, Fsd and Fcv). All of the human pressure indicator variables were also considered as predictor variables, i.e., DistWeir, DistRese, Struct, Urban, Rubble, Weirinf, Agric and Vfor. The response variables were: floristic composition, biotic variables (from the flora dataset), instream habitat characteristics (Dmean, Dmax, Wwid, substrate types, water surface patterns, riverbed stability and shading) and the total scores of the QBR and IHF and their subindices (except for Tgeo and Stype).

4.3.7 Data analyses

To meet objective A, a hierarchical cluster analysis and non-metric multidimensional scaling (NMDS) were performed using the PC-ORD v.4 statistical package (McCune and Mefford, 1999). The cluster analysis allowed the grouping of study sites according to their similarity in floristic composition. Bray-Curtis distance along with group average was used as a linkage method. The cluster tree was cut off to find a balance between the number of groups and their internal homogeneity, thus obtaining a level of aggregation appropriate for our objectives. All of the species surveyed during the field campaign remained in the flora matrix. Although deleting rare species is recommended when extracting patterns with multivariate analysis, it is not appropriate to analyse species richness or to examine patterns in species diversity. No transformations were applied to the data matrix.

NMDS gives a multidimensional result. The number of iterations (small steps for adjusting the position of the *n* entities or sites in the ordination space) to obtain the minimum stress value was 35. *Stress* is a measure of departure from monotonicity in the relationship between the dissimilarity (distance) in the original *p*-dimensional space (number of attributes) and the distance in the reduced *k*-dimensional ordination space (axes). According to McCune and Grace (2002), most ecological community datasets have solutions with a stress between 10 and 20, and values in the lower half of this range are quite satisfactory. The stress patterns in the data were analysed to select the number of appropriate dimensions for the final ordination. Then, the final dimensionality was selected by inspecting the stress value associated with new axes on the ordination (only one in this case). A Monte Carlo test of significance was included. NMDS allows correlation of variables in a second matrix with the ordination scores (McCune and Grace, 2002). In this study, NMDS was used as the base to relate the floristic matrix with the matrix of the biotic variables (calculated from the flora database) and QBR subindices (all of which were response variables). The distance used was Bray-Curtis.

The same procedure was carried out to meet objective B; i.e., cluster analysis and NMDS were performed to identify the relationships between instream habitat characteristics and IHF subindices. In this case, the response variables considered for the clustering and the main matrix of NMDS were Dmean, Dmax, Wwid, substrate types, water surface patterns, riverbed stability and shading. The minimum stress value was obtained after 40 iterations, indicating a reliable ordination with just one dimension. Before the analyses, data were transformed to make units of different attributes comparable. Thus, the data matrix was transformed so that data in percentages (range 0-100) were in the range of 0-1. Then, an arcsine square root transformation was applied to these variables, and finally, a general relativisation by variable was applied to all of the variables, including those that were not in percentage format. The cluster analysis allowed grouping of study sites according to their similarity in instream habitat characteristics. Euclidean distances along with group average as a linkage method were used in this case. The same transformed main matrix was used in NMDS, and the final ordination was correlated with a second matrix composed of the IHF subindices.

Graphical and testing methods were used to explore the classification strength (Van Sickle, 1997) based on dissimilarity with the tool *EnvClass* (Snelder *et al.*, 2009) in the statistical program R (R Development Core Team, 2008). The results are shown in a dendrogram of dissimilarity for the floristic and habitat groups. The vertical line (trunk) indicates the mean of all between-group dissimilarities ($\overline{B}$). The length of the horizontal lines (branches of the dendrogram) represents the between-group dissimilarity minus the within-group dissimilarity ($\overline{Wi}$), i.e. $\overline{B}-\overline{Wi}$. The larger the value of $\overline{B}-\overline{Wi}$ for the length of a branch to the left side, the more homogeneous the group is in relation to the whole dataset. The classification strength was evaluated with the indicator CS ($CS=\overline{B}-\overline{W}$). According to Van Sickle and Hughes (2000), CS values can range from 0, implying equal dissimilarity within and between classes (i.e., no class structure: $\overline{W}=\overline{B}$), to 1, implying no dissimilarity within classes (i.e., $\overline{W}=0$) and maximum dissimilarity between classes (i.e., $\overline{B}=1$).

Two canonical correspondence analyses (CCA) were carried out with the statistical program R to meet objective C; i.e., the first was performed to determine the main factors controlling the riparian floristic composition and quality and the second to determine the main factors controlling instream habitat characteristics and quality. Due to the large number of predictor variables in comparison with the number of study sites (16), a pre-selection was carried out using Spearman rank correlations to discriminate between relevant ($r > |0.7|$, $p<0.05$), irrelevant and redundant variables. This analysis was performed using SPSS v.16 (SPSS, 2007). A pre-selection of the response variables was also performed, and those that were irrelevant or redundant were not included in the CCA to avoid overlapping and make the plot clearer for interpretation. Nevertheless, the redundant variables were taken into consideration in the interpretation of the environmental gradients observed in the CCA plots.

4.4 RESULTS

The QBR and IHF indices described a similar longitudinal trend along the river (**Figure 4.5**). None of the 16 study sites was qualified as excellent by QBR; three of them were good (sites 5, 6, 9); seven had moderate quality (1, 2, 3, 4, 7, 8, 10); two were poor (11, 12); and four had bad quality (13, 14, 15, 16). Thus, 18.8 % of the study sites were considered to be well conserved, 43.8 % acceptably conserved and the remaining 37.5 % badly conserved.

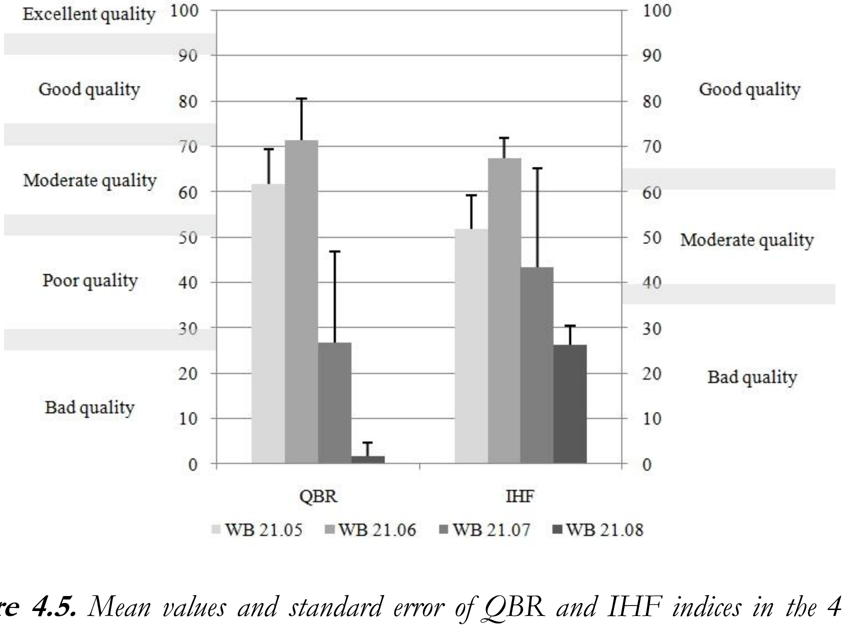


Figure 4.5. *Mean values and standard error of QBR and IHF indices in the 4 water bodies studied in the Serpis River. The quality ranges associated with each index are indicated.*

For the IHF index, 50 % of the study sites presented good quality (sites 4, 5, 6, 7, 8, 9, 10, 11), 25 % moderate (1, 2, 3, 12) and 25 % bad quality (13, 14, 15, 16). The longitudinal trend of the IHF values along the river was not as remarkable as that observed for QBR (**Figure 4.5**). With respect to individual water bodies, the first and second water bodies downstream of the dam exhibited moderate and good quality, respectively, for both indices, while the third had poor riparian quality and moderate habitat quality, and the fourth presented bad quality in both indices.

4.4.1 Floristic composition and riparian habitat quality

A total of 117 vascular plant species were identified at the 16 sites; 22 of the species (18.8 %) were not native to the region. At sites 15 and 16, only 58 % and 64 % of the species were native, respectively. Sites 3 and 5 showed the opposite trend, with only 8 and 9 % exotic species being found, respectively. A negative correlation was identified between P.Natives and DistRese ($r = -0.829$, $p < 0.001$); this correlation was also valid for Elev and Area (both correlated with DistRese).

The cluster dendrogram was trimmed at the level of 3 groups for the flora dataset (**Figure 4.6 A**). This level of grouping provided a good compromise between loss of information (about 31 % retained) and interpretability of the floristic similarities among sites. Two large branches were apparent in both dendrograms (flora and instream habitat), with one gathering the vast majority of the sites with bad riparian and habitat quality (mainly, sites in WB 21.08), while the remaining sites were included in the other branch. Regarding the similarities of the observed floristic patterns (**Figure 4.6 A**), sites 6 and 7 (in WB 21.06) were the most similar. Group 1 was formed by sites1-4, group 2 by sites 5-11 and group 3 by sites 12-16. It was especially noticeable that groups were formed by consecutive sites, which suggests that the changes in floristic composition were gradual along the river.

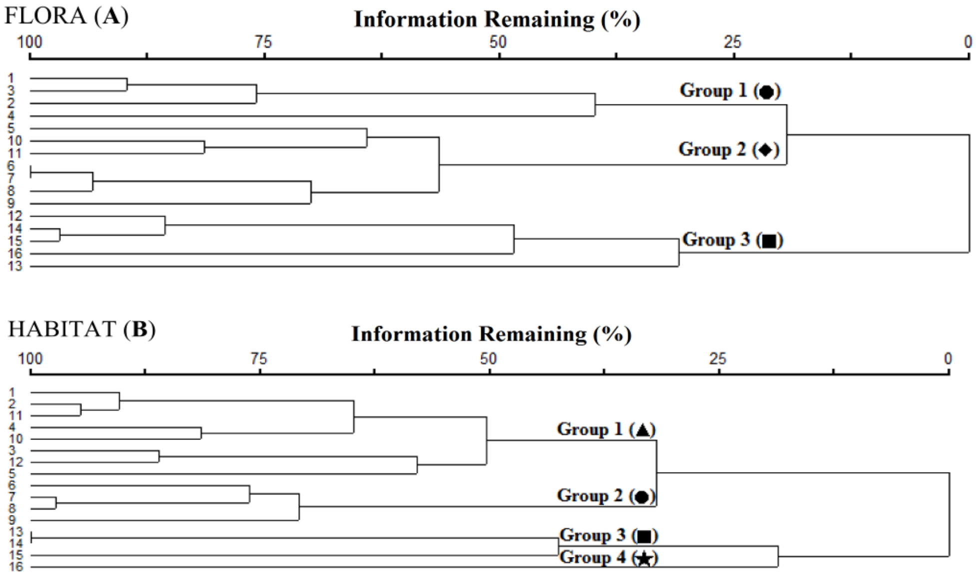


Figure 4.6. *A) Hierarchical cluster dendrogram based on floristic composition (group average clustering with Bray-Curtis distance). B) Hierarchical cluster dendrogram based on instream habitat characteristics (group average clustering with Euclidean distance). In both dendrograms, the numbers on the left correspond to study sites. Selected groups of sites are indicated; symbols coherent with* ***Figure 4.10*** *and* ***Figure 4.11****.*

The final stress for the NMDS analysis of flora data was 11.88, indicating a reliable ordination of sites according to their floristic composition (McCune and Mefford, 1999). NMDS indicated a gradient in the species composition (plot not shown in this article) and revealed the same pattern in the ordination of sites as in the cluster: the sites were ordered from those with good riparian habitat quality, located below the dam and in the gorge, to those with bad quality, near the river mouth, at the other side of the ordination. One dimension alone explained 89.9 % of the variability in the flora dataset.

The riparian species that were dominant at the extreme of this gradient associated with sites with good riparian quality were the following: *Rorippa nasturtium-aquaticum* (-0.601), *Nerium oleander* (-0.609), *Scrophularia valentina* (-0.666), *Samolus valerandi* (-0.672), *Salix atrocinerea* (-0.699), *Apium nodiflorum* (-

0.702), *Dorycnium rectum* (-0.715), *Potamogeton pectinatus* (-0.737) and *Smilax aspera* (-0.823). To the other extreme (i.e., in the direction of bad riparian quality), these species were: *Parietaria judaica* (0.619), *Ricinus communis* (0.629), *Arundo donax* (0.664), *Verbena officinalis* (0.671), *Calystegia sepium* (0.707), *Paspalum distichum* (0.778) and *Xanthium echinatum* (0.893). Generally speaking, the first species mentioned are natives and the last are exotics. **Figure 4.7** and **Figure 4.8** illustrate some examples of plants associated with sites with good and bad riparian quality, respectively.

Figure 4.7. *Examples of plants associated with sites with good riparian quality: Apium nodiflorum (a), Nerium oleander (b), Potamogeton pectinatus (c) and Salix atrocinerea (d).*

In addition, the strongest Pearson correlations among the first dimension of NMDS (representing floristic pattern) and the biotic variables corresponded to P.Exotics (0.857), PerennH (-0.891), Hydroph (-0.828), Richness (-0.763), Natives (-0.828), P.Natives (-0.857), QBR (-0.811) and QBR3 (-0.822). The other QBR subindices were not strongly correlated with the floristic composition.

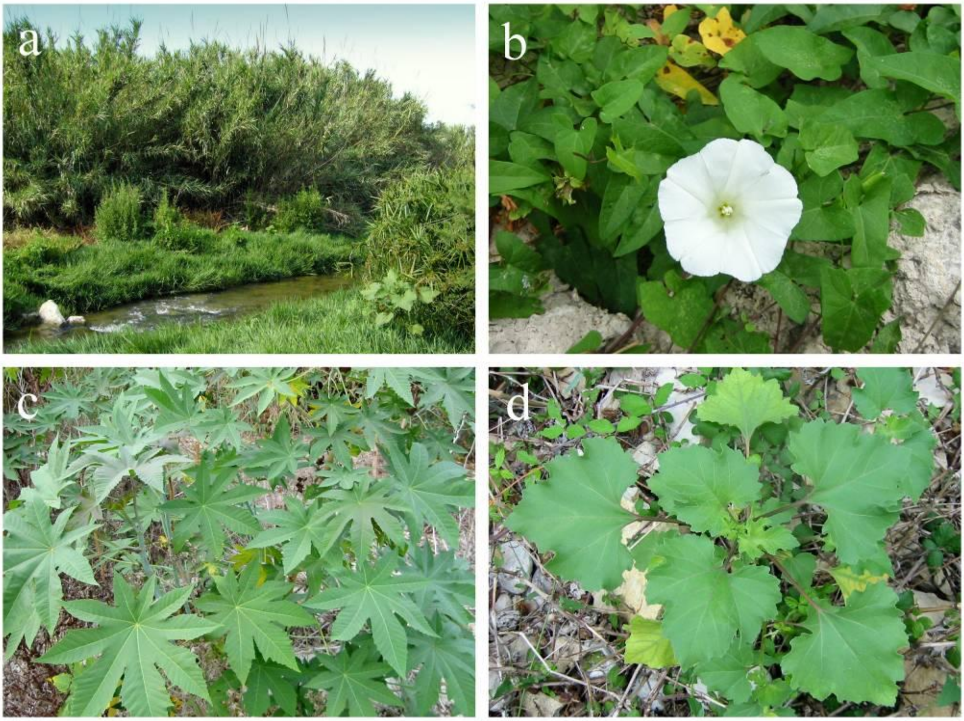


Figure 4.8. *Examples of plants associated with sites with bad riparian quality: Arundo donax (a), Calystegia sepium (b), Ricinus communis (c) and Xanthium echinatum (d).*

The classification strength was 0.24, indicating that classification of the sites into 3 groups was appropriate (Van Sickle and Hughes, 2000) because they were compact and homogeneous (**Figure 4.9 A**). In general terms, the first group (sites 1-4) was characterised by a high diversity of Natives, in particular Hydroph and PerennH; in the second group (sites 5-11), Trees and Ferns showed greater abundance than at other sites and a high diversity of Natives; the third group (sites 12-16) presented higher values for P.Exotics and AnnualH. Regarding riparian habitat quality, the first group exhibited QBR values in the range of 55-70 (median 62.5; SD 6.5), the second group between 45-85 (median 70; SD 13.5) and the third group between 0-30 (median 5; SD 12.5).

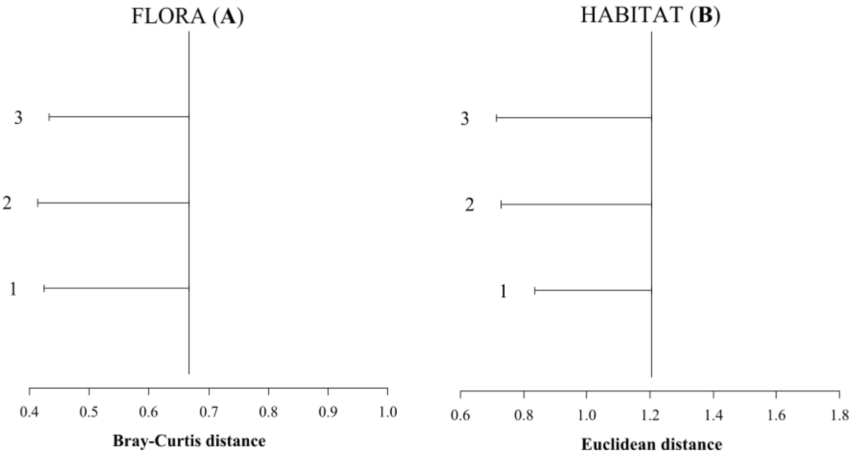


Figure 4.9. *Dendrograms of the groups identified in the cluster analysis based on the floristic composition of the riparian habitats (5A, left) and instream habitat characteristics (5B, right) at the 16 study sites of the Serpis River, East Spain. The mean inter-group dissimilarity is indicated at the foot of the vertical line (trunk); the difference between the inter-group dissimilarity and within-group mean dissimilarity (Wi, end of the branch) is represented by the length of the horizontal line (branches).*

4.4.2 Instream habitat characteristics and fluvial habitat heterogeneity

Four groups were defined based on similarities in instream habitat characteristics (**Figure 4.6 B**), retaining 42.5 % of the information. Sites 13 and 14 were the most similar, corresponding to the last site in WB 21.07 (hydrologically altered WB) and the first in WB 21.08 (hydrologically and morphologically altered WB). Group 1 was formed by sites 1-5 and 10-12, group 2 by sites 6-9, group 3 by sites 13-15 and group 4 only by site 16, which was identified as clearly different than other sites. Only two of the groups (3 and 4) were formed by consecutive sites.

The final stress for the NMDS analysis of instream habitat characteristics data was 11.52, indicating a reliable ordination of sites according to their instream habitat characteristics (McCune and Mefford, 1999; McCune and Grace, 2002). One dimension was obtained as the best solution, representing 89.6 % of the variance. The sites were distributed in the space defined by the habitat characteristics with a similar distribution to that revealed by the cluster tree. As with the flora data, there was a clear separation between groups of sites with different instream habitat quality.

The habitat characteristics most correlated with the first dimension, which best defined the extremes of the gradient, were in the following order (toward the sites with good instream habitat quality): Shade1 (-0.697), Shade2 (-0.703), B (-0.705), Flow3 (-0.795), Dmax (-0.822), Dmean (-0.846) and Flow2 (-0.858). To the other extreme, the variables were CL (0.758), SI (0.763), NoShade (0.786) and NoFlow (0.875). This quality gradient described by the habitat characteristics was strongly correlated with the total IHF value (-0.896) and the subindices IHF1 (-0.856), IHF2 (-0.838) and IHF4 (-0.755). The other IHF subindices were not strongly correlated with the instream habitat characteristics.

The classification strength was 0.42, indicating that classification of the sites into 4 groups was appropriate (Van Sickle and Hughes, 2000) because the groups were compact and homogeneous (**Figure 4.9 B**). The fourth group does not appear in the dendrogram because it was comprised of only one site. The first group included sites immediately downstream of the dam (sites 1-5) and those just below the gorge (sites 10-12); they were characterised by a wide water surface (high values of Wwid), slow flow pattern (Flow1), substrate dominated by CB and GR, stable riverbed (Stab2) and moderate shading (Shade1). The second group (sites 6-9) corresponded to the sites located in the gorge, which were characterised by more shading (Shade2), greater water depths (Dmean and Dmax), harder substrates (R, BB and B) and dominance of medium and fast flow patterns (Flow2 and Flow3). The third group (sites 13-15) incorporated the sites closer to the river mouth, with finer substrates (predominance of FG, SA and SI) and an absence of shading (NoShade). Finally, the fourth group (site 16) was characterised by even finer substrates (SA, SI and CL), soft river stability (Stab4) and an absence of shading and water flow (NoFlow). Regarding instream habitat quality, the first group presented IHF values between 45-64 (median 61.5; SD 8.4), the second group between 65-76 (median 68.5; SD 5.1), the third group between 20-25 (median 23; SD 2.5) and the fourth group was characterised by a value of 31.

For both flora and instream habitat, it was not possible to test for differences among groups in relation to the biotic variables or QBR and IHF subindices, respectively, because the sample size in the groups was smaller than 5 sites in some cases, which is the minimum, for instance, to carry out a non-parametric Kruskal-Wallis test.

4.4.3 Variable reduction

The number of predictor variables (geographical, hydrological, geomorphological and human pressures) was reduced from 21 to 12 based on the non-parametric correlations. Elev, DistRese and Area were considered redundant ($r = 1$, $p < 0.000$), and Area was selected for the CCA because this variable showed a stronger correlation with the axis CCA1. Moreover, a perfect correlation was found ($r = 1$, $p < 0.0001$) between Fmax and Fsd; thus, only Fmax was included in the CCA. Fmax and Fper95 presented a moderate correlation ($r = 0.731$, $p < 0.01$) but both of them showed a strong correlation with the axis CCA1. Due to their similar meaning, only Fmax was retained for the CCA. A high correlation existed between Fper10 and Fmin ($r = 0.944$, $p < 0.0001$). In this case, only Fper10 was considered because its correlation with other variables achieved a higher level of significance in some cases. SlopeArea was considered irrelevant because it showed no strong correlation with any other variable. It only showed significant, but not strong correlations with DistWeir ($r = -0.676$, $p < 0.01$) and Agric ($r = 0.530$, $p < 0.05$). The reason for this is that the sites where the watershed mean gradient was higher corresponded to the gorge, where weirs are more abundant, and similarly, where this gradient was lower, it corresponded to flatter areas, which are more suitable for agricultural use. The human pressures Weirinf and Agric were also considered to be irrelevant because they were not related to other variables. Fmean was considered irrelevant because of its lack of strength in the CCA and due to presenting no correlation with other riparian or instream habitat variables. It was only correlated with Area and other hydrological variables; however, it showed significant but not strong correlations with QBR3 ($r = 0.639$, $p < 0.01$) and Exotics ($r = -0.649$, $p < 0.01$). Finally, the most relevant predictor variables considered in both CCA plots were Area, SlopeReach and DistWeir (geographical), Fper10, Fmax and Fcv (hydrological), Tgeo and Stype (geomorphological) and Vfor, Struct, Rubble and Urban (human pressures).

Although there was no restriction on the number of response variables that could be shown in the CCA, those considered to be irrelevant (appearing overlapped in the centre of the plot, $r < 0.1$ for the first two axes) or redundant (overlapped with others) were not included. The variables rejected were QBR1, QBR2 and QBR4 (irrelevant, not related to floristic composition), Ferns and P.Ferns (not correlated with others), PerennH, Shrubs, P.Natives, P.Hydroph and Richness (low correlation with the first two axes). Trees and P.Trees appeared overlapped. Only Trees was retained because it was correlated with more variables. The variables rejected in the CCA for the instream habitat characteristics were IHF3, IHF5, IHF6 and IHF7 (irrelevant, did not appear to be correlated with instream habitat characteristics in NMDS and actually showed a weak correlation with the first two CCA axes). Dmean and Dmax appeared overlapped because they exhibited a similar performance and similar correlation with CCA1. Only Dmean was retained for the analysis.

4.4.4 Factors controlling riparian habitat quality

The first two axes of the CCA for biotic variables and riparian habitat quality explained 83 % (79 %-axis1 and 5 %-axis2; **Figure 4.10 A**) of the cumulative variance in the response variables.

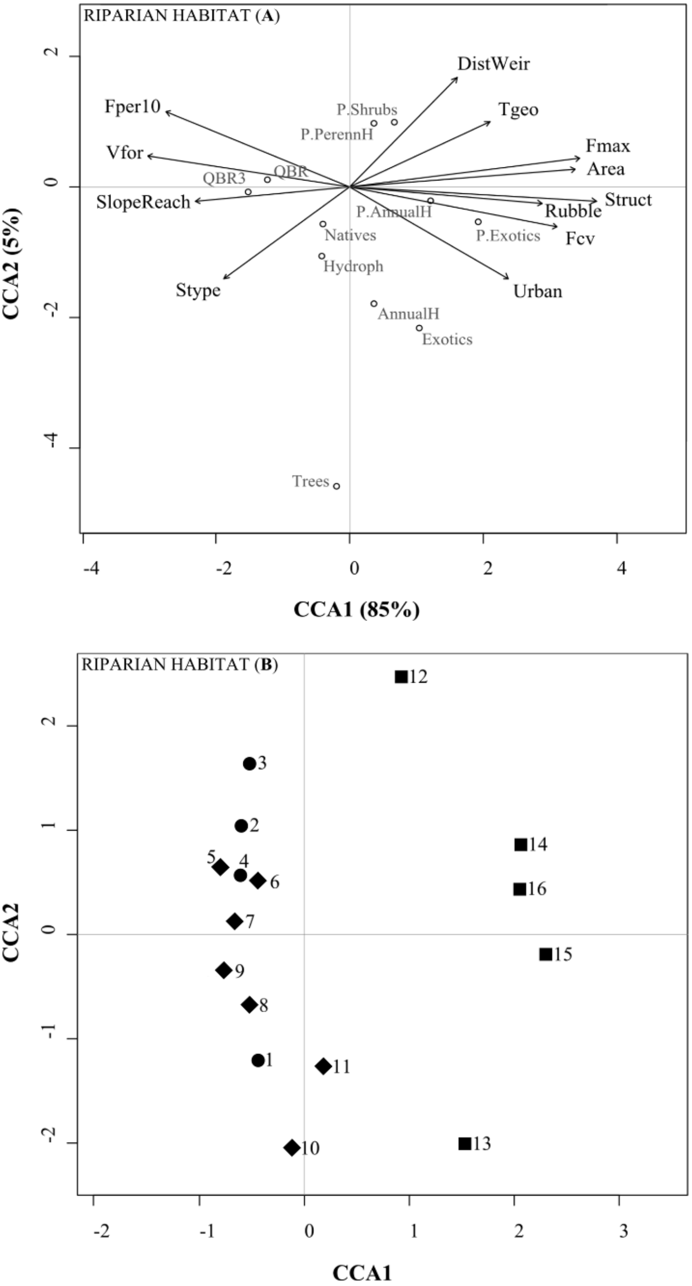


Figure 4.10. *CCA ordination diagram to analyse riparian habitat, showing the distribution of the biotic variables and* Q*BR subindices (A, in grey colour) and study site*

positions (B) in relation to predictor variables (geographical, hydrogeomorphological and indicators of human pressures, black arrows) in the space represented by the first two axes, which explain 90 % of the data variability. The length of the arrows indicates the strength of the variable in that dimensionality of the solution, pointing towards the positive gradient. For brevity, the codes are indicated in the text. Only loadings >|0.70| were considered for interpretation. The symbols in B indicate a cluster's group membership (see ***Figure 4.6 A****).*

The predictor variables (geographical, hydrological, geomorphological and human pressures) explained 90 % of the riparian habitat characteristics with the first two axes. Axis 2 represented a small proportion of the data variability and did not show an interpretable pattern. The variables positively related to axis 1 were Struct (0.97), Fmax (0.91), Area (0.89), Fcv (0.82) and Rubble (0.76), while Vfor (-0.80) and Fper10 (-0.73) were negatively related. The QBR subindices were located opposite to the human pressures. No predictor variables had strong loadings on the second axis. Among the response variables, the strongest was P.Exotics (0.72). The positioning of variables and sites on the CCA plot showed a strong quality gradient, especially represented by axis 1, which divided the study sites into 2 groups (**Figure 4.10 B**). The most altered sites (belonging to cluster group 3) were found on the right side of the ordination, and those with good and moderate quality were located on the left side (cluster groups 1 and 2).

4.4.5 Factors controlling instream habitat quality

The first two axes of the CCA explained 60 % (44 %-axis1 and 16 %-axis2; **Figure 4.11 A**) of the cumulative variance in the response variables. The predictor variables explained 67 % of the instream habitat characteristics and quality in the first two axes. Not all of the predictor (constraining) variables contributed in the same way; the vast majority of them showed a stronger ordination in the first axis than in the second. The only positively related variable was Vfor (0.73), whereas the negatively related variables were Struct (-0.93), Fmax (-0.89), Area (-0.84) and Fcv (-0.71). No predictor variables gave strong loadings on the second axis.

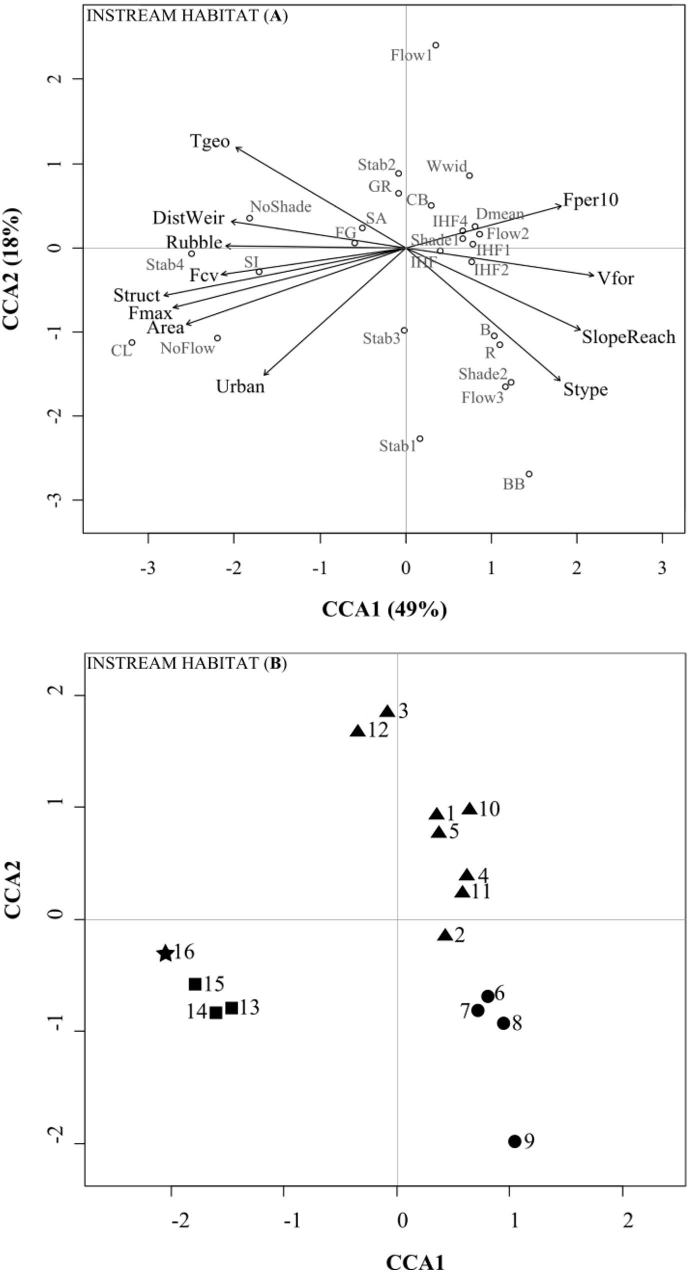


Figure 4.11. *CCA ordination diagram to analyse instream habitat, showing the distribution of instream habitat characteristics and the IHF subindices (A, in grey colour)*

and study site positions (B) in relation to predictor variables (geographical, hydrogeomorphological and indicators of human pressures, black arrows) in the space represented by the first two axes, which explain 67 % of the data variability. The length of the arrows indicates the strength of the variable in that dimensionality of the solution, pointing towards the positive gradient. For brevity, the codes are indicated in the text. Only loadings >|0.70| were considered for interpretation. The symbols in B indicate a cluster's group membership (see ***Figure 4.6 B****).*

Among the response variables, those that were more positively related to the first axis were BB (0.92), Shade2 (0.79) and Flow3 (0.74); whereas those that were more negatively related were CL (-2.02), Stab4 (-1.58), NoFlow (-1.39), NoShade (-1.16) and SI (-1.08). The only variable positively related to the second axis was Flow1 (0.92), and those negatively related were BB (-1.04) and Stab1 (-0.88). The IHF subindices were located opposite to the human pressures. The study sites showed a clear distribution in the CCA (**Figure 4.11 B**); those that were more altered and with lower habitat quality were located on the bottom left (cluster groups 3 and 4, in **Figure 4.6 B**), whereas those with good and moderate quality were found on the right side of the ordination. The sites in cluster 1 were in the positive region of the second axis, and the sites belonging to the cluster 2 were located in the negative region.

4.5 DISCUSSION

4.5.1 Riparian and instream habitat quality downstream of the Beniarrés dam

In the present study, we were interested in the gradual changes in riparian flora and certain instream habitat characteristics in a hydromorphologically altered river ecosystem; these changes were also related to the QBR and IHF indices, which are the indices most widely used by Spanish water administrations (Aguilella *et al.*, 2005; ACA, 2006). Our results provided a clear picture of the hydromorphological conditions in consecutive segments downstream of a large dam. It was possible to distinguish a gradient in the riparian and instream habitat quality, clearly defining the extremes formed by two groups of sites: those with good and moderate quality (below the dam and in the middle course) and those in the lower course, where the degradation of the river and its banks was more notable, and the riparian and habitat quality were lowest. More specifically, a wider and more laterally active channel characterised the sites located in the first WB, with little variability in the flow regime and no periods of null flow and where the vegetation was diverse and natural. The surrounding area was a mosaic of farmlands and natural forests. The sites in the second WB showed less influence of regulation and were hydromorphologically constrained by the characteristics of the gorge (higher slope, harder substrate and more stable riverbed). There were no significant human pressures associated with this water body and there was a connection among aquatic-riparian-terrestrial vegetation, which was a relevant characteristic for obtaining a high riparian quality. Despite the hydrological alteration of this area, the increase in quality could be explained by its low accessibility and the low level of intervention in the surrounding area. Other studies in Mediterranean rivers (Suárez *et al.*, 2002) have determined that sites with better structured riparian forests are located in inaccessible stretches, generally localised in gorges and in headwaters (Palma *et al.*, 2009).

The third WB was located at the transition between the gorge and the coastal plain. The river becomes wider again in this region, and there was space for well-developed riparian forests. Because the sediment became finer in this area, the floodplain was more prone to agricultural use. Finally, sites within the fourth WB, which was entirely located in the plain, presented higher flows in the wet season (higher Fmax) but were also associated with periods when the channel was completely dry (NoFlow). A lack of water during part of the year disrupted the fluvial connectivity in this area and made some aquatic habitats unsuitable for the fish fauna. This water body suffered the pressures of water abstractions more intensely than the other water bodies and in addition, the morphological degradation (associated with the presence of lateral structures and urban uses in the floodplain) was also more intense. These alterations have resulted in reduction of riparian and habitat quality and impoverishment of vegetation (with a stronger presence of annual herbs and exotic species being observed). Recent studies in Catalonian Mediterranean rivers have emphasised that excessive water abstraction impairs their capacity to support native biota (Benejam *et al.*, 2010), as can happen at these sites near the river mouth.

4.5.2 Longitudinal variation of the flora and hydromorphological indices

The total QBR score and the vegetation cover quality (QBR3) were the elements most correlated with the floristic composition. It makes sense because QBR3 evaluates components such as diversity of native trees and shrubs, presence of exotic species and riparian continuity along the river corridor, taking into account the geomorphological river type in the scoring. The highest riparian quality was found at those sites associated with less intervention in the surrounding area (predominately Vfor) and a higher slope in the river and in the riparian environment (Tgeo 1-closed and 2-midland). The other subindices, which refer to the percentage of vegetation cover (QBR1), structure (QBR2) and river channel alterations (QBR4), were not strongly correlated with the floristic composition; in the study area, the variability of these subindices and their relationship with habitat degradation was not relevant, but in other rivers, they could play an important role. In this Mediterranean river, natural processes may be limiting the development of a climax riparian forest as well as the structure and cover; therefore, the QBR score could be underestimating the conservation status of the study area because it is not possible to reach high values. Thus, it would be advisable to compare the deviation of the values to a geomorphological reference (Suárez *et al.*, 2002) or to apply the modified QBR (Costa, 2006) defined for rivers in more arid conditions, which introduces modifications in the scoring of the subindices from the original version from Munné *et al.* (1998).

Regarding IHF, the most significant correlations with instream habitat characteristics were found in total IHF score, riffle embeddedness or sedimentation in pools (IHF1), riffle frequency (IHF2) and flow velocity/depth regime (IHF4). The other subindices showed a low correlation, but the characteristics they referred to were important along the gradient described; e.g., the substrate type (implicit in IHF3) or shading (IHF5) clearly reproduced the gradient, corresponding at one extreme to sites with a hard substrate and dense shading and at the other extreme to sites with a finer substrate and without shading.

The changes in the instream habitat among the 16 sites were more prominent than the changes in the floristic composition, which varied gradually along the river (CS values). This can be explained because the river flows through different geomorphological environments, and the gorge is a hydrogeomorphological and floristic discontinuity that induces greater diversity in the study area. According to Braatne *et al.* (2008), geomorphic transitions are naturally associated with ecological changes. However, the river is classified as the same ecotype throughout all of this area. This suggests that it would be advisable to reclassify the gorge into a different ecotype because regular inventories could confound these naturally higher scores with recovery from hydrological alteration or other pressures. Similarly, the thresholds applicable to the quality classes for the indices could be different than those applied in the reaches upstream or downstream of the gorge. Other studies (Braatne *et al.*, 2008) have concluded that habitat heterogeneity is very different between river types, and in some cases, larger differences have been found than among reference and non-reference sites within a river typology (Barquín *et al.*, 2011).

We suggest that instead of using fixed characterisations of some indices, it could be useful to employ an open characterisation for certain riparian attributes and then measure the deviation of those riparian attributes from the geomorphological reference condition. This system would be simpler to apply and could be more transferable across regions in comparison with the large variety of indices currently developed in Europe and in the Iberian Peninsula. One basic variable that should be included in such assessments is the presence and extension of recruitment in a site (not included in the QBR). This is one of the main functions affected by the management of large dams (Auble *et al.*, 1997; Mahoney and Rood, 1998b) and has recently been included in some indices, such as RQI (González del Tánago *et al.*, 2006; González del Tánago and García de Jalón, 2011) and RFV (Magdaleno *et al.*, 2010). Another weakness identified in QBR is related to the percentage of cover in the riparian area, as it is evaluated with a higher score when the percentage of cover increases. However, below a dam, the cover increases in many cases as a consequence of flood regulation and vegetation encroachment, rather than because of improvement of ecological status; therefore, this variable is not always related to the natural status of a riparian zone (Rood and Mahoney, 1995; Wilcock *et al.*, 1996).

4.5.3 Factors controlling riparian and instream habitat quality

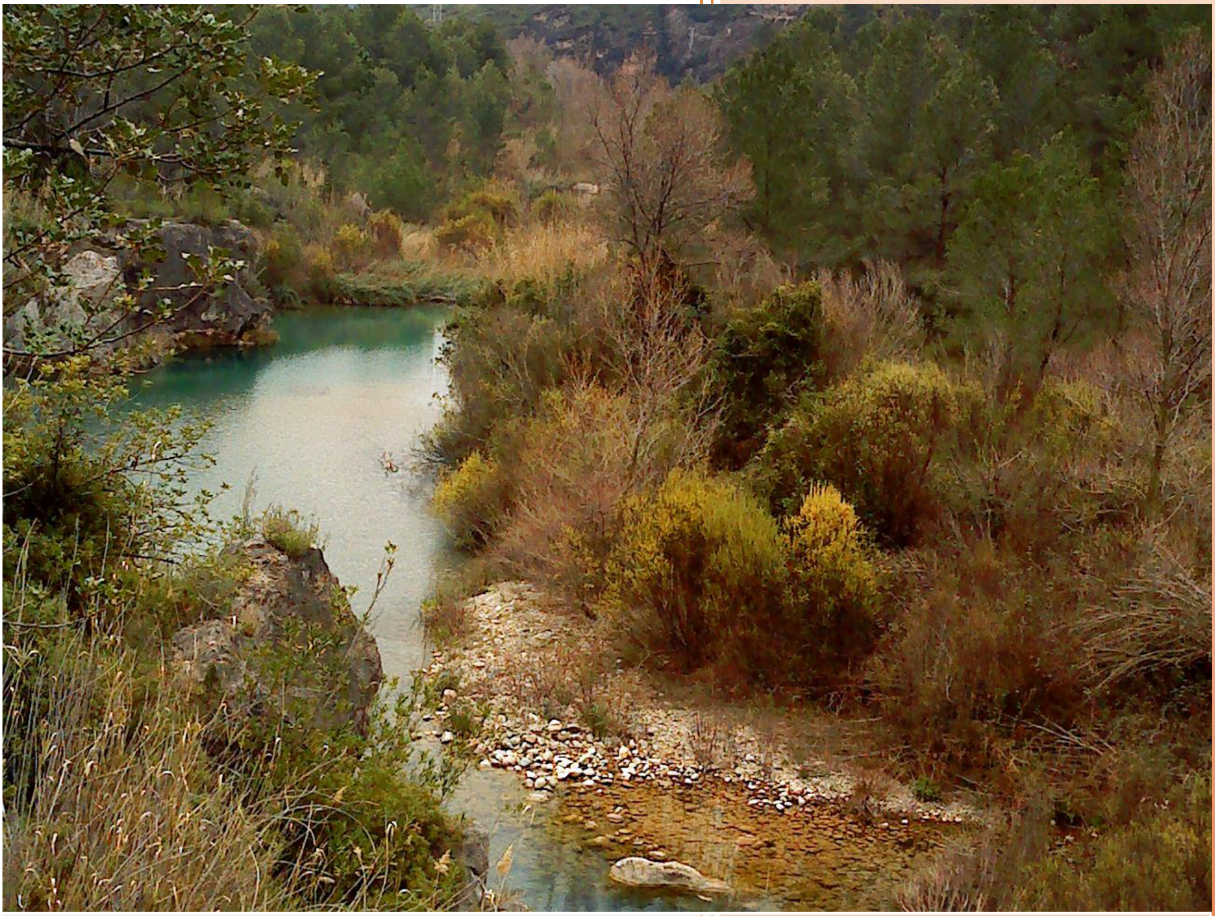
Our results revealed the importance of maintaining at least a minimum flow during the year along the entire river length because the sites with lower (or even null) Fper10 values exhibited bad quality. These degraded sites also experienced the highest flow values (Fmax) because large flows are related to a larger watershed area, but this variable was not related to hydromorphological quality in this study. Apart from the extreme values, the flow variability deserves special attention. Observation of the flow regime before and after regulation indicated that flows have been reduced in both magnitude and variability. The hydrograph at Lorcha is now inverse and plain; i.e., the highest water levels appeared in the summer months and the lowest in winter. Additionally, the natural fluctuation during the year has disappeared. Alteration of typical variability in natural flows due to dams has also been observed in other Mediterranean-type rivers of eastern (Vidal-Abarca *et al.*, 2002) and central Spain (Baeza *et al.*, 2003). A general reduction of flows due to dam operation has important consequences because it disconnects riparian zones from riverine influence (Magilligan *et al.*, 2003). However, the natural autumnal floods downstream of the dam were extremely large in some years, with contributions from unregulated tributaries in the lower basin. Therefore, the high values of variability in this area are a consequence of the large differences between artificial low flow periods (due to water regulation and abstraction) and natural floods that are not retained in the reservoir. In unregulated Mediterranean rivers, flow regimes are naturally highly variable (Gasith and Resh, 1999), but in the case of the Serpis River, this variability is a consequence of dam regulation and natural events.

Another important issue is the occurrence of large floods, which have triggered channelization of the river course (Segura-Beltrán and Carmona-González, 1999), especially in the lowest region of the Serpis River. Thus, the presence of lateral structures (Struct) has been established as one of the main pressures affecting the riparian and habitat quality in this area. The low quality in the lower course was also related to the presence of urban uses because many of these structures were planned for urban protection. The high correlations found between Fmax and NoFlow and with the presence of rigid lateral structures in the channel (Struct) seem to be the reasons for the increase in the presence of exotic species at the lowest sites. According to Tabacchi *et al.* (1998) and Naiman *et al.* (2005), colonisation of the lower parts of rivers by exotic species is a major consequence of the interaction between natural (hydrological) and human-induced disturbances. In general terms, the stronger the anthropogenic impact on the land, the more successful the dispersion and encroachment of exotic species (Lodge, 1993; Poff *et al.*, 1997). This finding is of note for the Serpis River, where not only the flow regulation, but its synergy with other human pressures near the river mouth has dramatically affected the riparian plant communities and the hydromorphological quality in the area. Similarly, other studies, (e.g., Wang *et al.*, 1997) have concluded that urban land use is more harmful to biotic communities than agricultural land use along margins. In the Serpis River, the pressure exerted by agricultural use (Agric) was not clear, although it was expected to play a role in the riparian and instream habitat quality. Forested land use (Vfor) affected river quality in a positive manner and was plotted very close to the indices.

Several measures to improve river quality can be derived from this study, such as the implementation of environmental flows designed with a more natural pattern, and with the aim of providing periodic high-flows events and maintaining minimum flows during irrigation periods. This study highlights the importance of reducing the human-induced periods of null flows and of recovering natural flow variability for improvement of hydromorphological quality. Another measure that should be considered would be to provide the river with more space and lateral mobility by removing some lateral structures (in places where flood risk prevention allows this measure) and incorporating abandoned agricultural plots into its banks.

From a general perspective, our results indicate the importance of science-based monitoring of river networks to meet the requirements of the Water Framework Directive, considering river geomorphology as a valuable feature. If this is not done, using the current system of ecotypes alone can lead to invalid comparisons among river segments with their reference sites. Certain geomorphological features can be more important of river quality than the mean flow or watershed area and should be considered in the evaluation and potential restoration of Iberian rivers.

Chapter 5



Six decades of changes in the riparian corridor of a Mediterranean River: A synthetic analysis based on historical data sources

5 SIX DECADES OF CHANGES IN THE RIPARIAN CORRIDOR OF A MEDITERRANEAN RIVER: A SYNTHETIC ANALYSIS BASED ON HISTORICAL DATA SOURCES

5.1 ABSTRACT

Riparian corridors in semi-arid Mediterranean environments are ecosystems of high biodiversity and complexity. However, they are threatened because of high levels of human intervention. River damming and related flow manipulation is considered as one of the most prominent human impacts on riparian corridors. This study combines historical time series information on river flows and their human manipulation, historical aerial images depicting changes in riparian land cover and ground observations of the species – age composition and morphology of the riparian corridor of a Mediterranean river (Mijares River, Eastern Spain) over the last 60 years. In this sense, we explored how to integrate information from a wide variety of data sources; we extracted a variety of indices and undertook analyses that identified and summarized spatio-temporal changes in the riparian structure and in the driving flow processes. Results revealed an increase in the cover and density of woody vegetation and a decrease in bare sediment areas (essential for recruitment of riparian pioneer species), with a synchronous reduction in the complexity of the riparian corridor of the middle reaches of the Mijares River. These vegetation changes have accompanied a decrease in the magnitude and variability of river flows over the last six decades, with higher severity since dam closure. This study illustrates the effectiveness of combining disparate historical data sources and the effectiveness of processing these sources to extract informative metrics that can improve the understanding and management of riparian systems.

Keywords: Riparian vegetation; flow regulation; semi-arid Mediterranean river; temporal evolution; landscape metrics.

5.2 INTRODUCTION

Riparian ecosystems have unique biodiversity and complexity (Naiman *et al.*, 1993; Naiman *et al.*, 2005), and they provide numerous benefits, such as food sources, ecological corridor, habitat and refugia for fauna, bank stabilization, improvement of water quality, temperature control and recreational value (Gregory *et al.*, 1991; Schuft *et al.*, 1999). However, riparian ecosystems are highly sensitive to disturbance and anthropogenic influences, and despite their value, they are threatened, especially in semi-arid Mediterranean environments (Salinas *et al.*, 2000). Historically, Iberian Mediterranean-type streams have been subject to high levels of human intervention including intensive agriculture and forestry, water abstraction, damming, grazing, mining, physical interventions on riverbanks and urban development (Aguiar and Ferreira, 2005; Hooke, 2006). Among all these human impacts, river damming and related flow manipulation is one of the most prominent (Naiman *et al.*, 2005; Petts and Gurnell, 2005; Petts and Gurnell, 2012), with significant negative consequences for the surrounding natural ecosystems and environment (New and Xie, 2008).

Depending on the degree of water regulation, changes in the quantity, timing and variability of downstream water flow may occur (Greet *et al.*, 2011), accompanied by changes in sediment transport and in the configuration of the riparian and wetland habitats (Rood *et al.*, 2005) resulting in a fragmentation of the river channel and its biotic populations (Dynesius and Nilsson, 1994). In the North American Great Plains (Katz *et al.*, 2005), dams typically have reduced both downstream peak discharge and sediment load, resulting in diminished stream power downstream and a narrower active river channel. When dams retain sediment and reduce discharge, in the long term, there is a reduction in the channel migration rate because those flows able to produce erosion and point bar deposition are no longer released (Friedman *et al.*, 1998; Johnson, 1998). In addition to this, gravel mining was carried out below the dams in many Mediterranean rivers, and the combination of the effects of both activities (mining and flow regulation) has produced an even larger sediment deficit (Batalla *et al.*, 2004; Kondolf and Batalla, 2005). In Spain in particular, gravel mining has been a common practice in rivers whose aggregates have been used in road and building construction, for example. The reduction in fluvial dynamism can provoke a reduction in the availability of bare sediment establishment sites for pioneer species (Rood and Mahoney, 1990) and hence, a decline of riparian forests on regulated reaches. Numerous references about this decline in semi-arid North American rivers have been reported since the 1980s (e.g. Groeneveld and Griepentrog, 1985; Howe and Knopf, 1991; Busch and Smith, 1995; Stromberg *et al.*, 1996; Patten, 1998; Williams and Cooper, 2005) and also more recently in the context of Mediterranean basins (Muller *et al.*, 2002; González *et al.*, 2010; González *et al.*, 2012). In many cases, this decline is preceded by a significant increment in riparian biomass (Johnson, 1994), although this new vegetation may be composed of exotic woody species (Johnson *et al.*, 1995; Dixon and Johnson, 1999). According to Azami *et al.* (2004), the degree of woodland development depends on the relationship between the timing of flood events and the rate of vegetative growth in the riparian zone.

Schuft *et al.* (1999) emphasized that the fragmentation and loss of complexity of riparian woodland reduce the efficient functioning of these ecosystems. In this sense, the management of riparian ecosystems, especially those in a Mediterranean climate, should take account of the importance of natural dynamism for maintenance of their biodiversity and ecological benefits (Ollero, 2007). It is, therefore, unsurprising that there is an increasing management interest in assessing the current integrity of the riparian corridor and the ways in which it may have changed through time (e.g. Aguiar *et al.*, 2010; Garófano-Gómez *et al.*, 2011b; González del Tánago and García de Jalón, 2011). The achievement of such assessments requires long-term observations (Nakamura and Shin, 2001). Although purpose-specific long-term observations are rarely available, sequences of aerial images of widely varying spatial resolution (obtained from airborne and satellite platforms) provide historical records that can be used to evaluate river channel and corridor dynamics (e.g. Bertoldi *et al.*, 2011a; Bertoldi *et al.*, 2011b). The analysis of such sequences of historical imagery provides an opportunity to quantify large-scale features at a landscape scale and extract a variety of integrative metrics (Apan *et al.*, 2002; Fernandes *et al.*, 2011). Nevertheless, aerial images are insufficient to reveal small-scale features (local-level approach), such as plant species and community types (Braatne *et al.*, 2008; Aguiar *et al.*, 2010). Therefore, ground-level images, field surveys and data collection in situ are usually necessary to provide this detailed information as well as to provide information from which interpretations of aerial data can be validated (e.g. Bertoldi *et al.*, 2011b).

This study combines historical time series information on river flows and their human manipulation, historical aerial images depicting changes in riparian land cover and ground observations of the age composition of woody species and morphology of the riparian corridor of a Mediterranean river, the Mijares River, Eastern Spain, over the last 60 years. The aim of this study is to quantify changes in river flow regime, river channel position and width and riparian land cover within two naturally functioning alluvial river reaches and to explore associations between these ecosystem characteristics. To achieve this, we made the following specific research contributions:

A. To integrate information from a wide variety of data sources including process time series, airborne imagery of contrasting spatial resolution and transect-based ground data.

B. To extract a variety of indices that summarize spatio-temporal changes in riparian structure and temporal changes in the stream flow regime.

C. Thus, to illustrate the effectiveness of combining disparate historical data sources and the effectiveness of processing these sources to extract informative metrics that can improve the understanding and management of riparian systems.

5.3 STUDY AREA AND SITES

The Mijares River rises at 1600 m above sea level in the Sierra de Gúdar (Teruel) and flows 156 km in a south-easterly direction to the Mediterranean Sea (**Figure 5.1**). Average annual rainfall and potential evapotranspiration in the basin are 550 and 722 mm, respectively (Quereda *et al.*, 2004), with maximum monthly rainfall typically occurring in October and minimum monthly rainfall in July (MOPREDAS database; González-Hidalgo *et al.*, 2011).

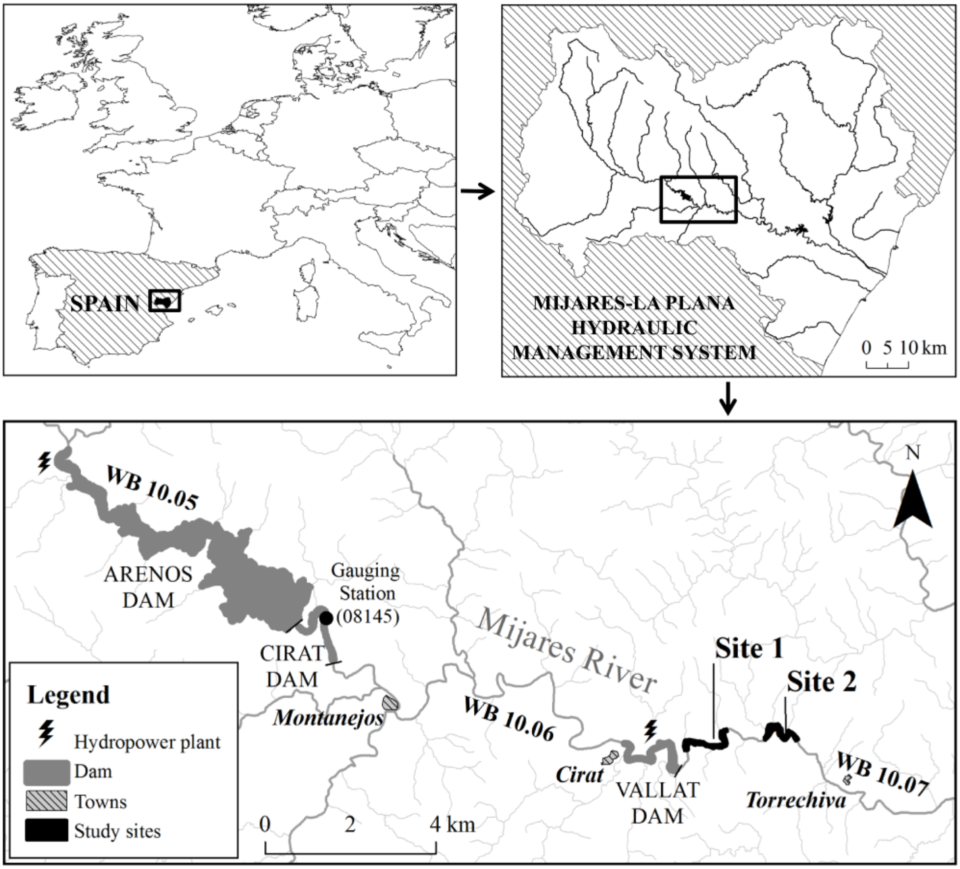


Figure 5.1. *Location of the study sites in the Mijares River, downstream of the Arenós, Cirat and Vallat dams (built in 1979, 1962 and 1968, respectively) in the Júcar River*

Basin District, Eastern Spain. Main towns of the study area and water bodies (WB) are also indicated.

The river's natural flow regime has an important groundwater component but is also irregular: with extremely low flows in summer; extraordinary floods in autumn, in response to heavy rain storms; and further variability resulting from snow melt.

Human actions have increasingly impacted the river's regime over the last 60 years as a result of changes in demographics, and demands for water for hydropower, agriculture, domestic and industrial consumption. The human population in the basin increased by 73 % during the 20th century, especially from 1960 onwards, driving an increasing demand for water. However, population dynamics have been spatially highly variable. For example, the middle basin has experienced a continuous decrease in population from 1900, whereas the population in the coastal area increased by over 90 % between 1940 and 2010 (Instituto Español de Estadística: http://www.ine.es/). These figures illustrate demographic movements from rural to urban areas as well as abandonment of farm land in the upper and middle basin, with remarkable agricultural intensification in the lower basin.

The total irrigated area in the basin has increased by 76 % since 1950, with a particularly high expansion since 1980. Water for irrigation is abstracted directly from the river (41 %) and pumped from groundwater (59 %). The course of the river is frequently interrupted by dams and weirs associated with water abstractions, of which the Arenós dam is the largest in the Mijares basin. This impoundment provides water to two hydropower plants Cirat and Vallat (built in 1962 and 1968, respectively), which, together with five other plants along the river, provide 13 % of the hydroelectric capacity in the Valencian region. As a result of these human activities, the maximum river flows in the lower basin now take place in August and September, and the aquifer has become overexploited; thus the lower part of the river loses water and sea water intrusion occurs near the coast, especially in drought periods (Quereda *et* *al.*, 2004). In addition, 26 % of the entire river length suffers hydromorphological impacts due to the management and presence of hydropower plants (CHJ, 2009a).

This chapter is concerned with the impact of the aforementioned activities on the riparian zone in the middle course of the river, which extends approximately 44 km downstream from the Arenós dam (**Figure 5.1**) and is upstream of the main area of population growth and intensification of agriculture. In this area, it is possible to observe changes in the structure of the riparian zone in response to increasingly severe river regulation over the 20th century, particularly since the 1960s, in a location where there is declining direct human pressure on the river margins. For this study to be carried out, a representative segment 4065 m long was selected in the middle course of the Mijares River, close enough to the main impoundments to isolate their impacts on vegetation, because farther downstream, additional factors become increasingly influential (agriculture, urbanization, quarries, etc.).

Three major properties of this segment are characteristic of the river's middle reaches, making the segment suitable for the purposes of the present analysis. First, the riparian habitat quality in this segment is classed as 'moderate' (Riparian Habitat Quality Index-QBR; Munné *et al.*, 2003), which is the same as 55 % of the middle river course (Aguilella *et al.*, 2005), with a limited presence of the invasive giant reed *Arundo donax* L., which is much more abundant in wider sections downstream. Second, the vegetation composition in this segment is also similar to the rest of the middle course (Aguilella *et al.*, 2007), consisting of the *Vinco difformis–Populo albae geosigmetum*, whose potential mature stage (*Vinco-Populetum albae*) corresponds to a forest dominated by white poplar (*Populus alba*) and black poplar (*Populus nigra*), and a willow shrub community (*Coriario myrtifoliae–Salicetum angustifoliae*) in the areas near the water's edge. Lastly, the sinuosity of the river segment, which is greater than 1.5, denotes a meandering pattern that is characteristic of the middle course. Within the study segment, two alluvial reaches were selected for detailed analysis (**Figure 5.1**), where the valley bottom and its alluvial sediments were sufficiently wide for the unrestricted development of riparian vegetation. The intervening reach was omitted because it is closely confined by hillslopes, limiting the potential for riparian woodland development. These two study sites are located between 310 and 340 m above sea level. **Table 5.1** summarizes their characteristics and their distance downstream from the outflows of three upstream dams (Vallat, Cirat and Arenós; **Figure 5.1**). The area studied at each site was delimited by the 500-year flood contour as computed by the Júcar River Basin Authority (CHJ, 2005b) with the 1D model MIKE 11 (Danish Hydraulic Institute, 2003) with upstream and downstream ends delimited by transects perpendicular to the main flow direction. This provided an objective and consistent method for delimiting each study site, which included the entire riparian corridor. Both sites were approximately 90 m wide (site 1, 60 to 120 m; site 2, 40 to 170 m). At both sites, the river bed is comprised of gravel and cobble-sized sediments, and the banks consist of sand, gravel and cobbles. Bedrock outcrops and large jagged boulders delivered from the adjacent slopes are frequent features of the river corridor and channel at both sites.

Table 5.1. *River length, catchment area, slope, sinuosity and distance along the river to upstream impoundments of the two study sites in the Mijares River, Spain.*

Site	River length	Catchment area (km^2)	Slope (%)	Sinuosity	Distance from dam(km)		
					Arenós	Cirat	Vallat
1	1640	1798	0.61	1.55	18.25	15.88	0.67
2	1410	1805	0.70	1.86	20.90	18.53	3.32

5.4 METHODS

5.4.1 River flow estimation and characterization of study sites

There is no long-term flow record for the Mijares River close to the study sites, thus several data sources (**Table 5.2**) were combined to estimate flow records for the periods between the 1956, 1976, 1997 and 2007 aerial images that were analysed to assess land cover change (see section on Changes in Land Cover Assessed from Aerial Images).

Table 5.2. *Summary of the sources of river flow data and their attributes used to estimate a monthly flow record for the study sites (for locations of dams, water bodies and a gauging station, see* ***Figure 5.1****).*

Data source	Period	Estimated maximum (hm^3/month)	Time scale	Description/source
Reconstruction of natural inflows at Arenós*	1940-1976	52.94	Monthly	Professor Juan Marco Segura** (unpublished data)
Simulation for water body 10.05	1940-2007	72.35	Monthly	Rainfall-runoff simulation with PATRICAL model***
Simulation for water body 10.06	1940-2007	130.68	Monthly	Rainfall-runoff simulation with PATRICAL model***
Arenós Gauging Station (below the dam; code 08145)	1987-2007	54.74	Daily	Júcar River Basin Authority
Water abstraction for irrigation	1940-2007	0.23	Monthly	Estimation considering Water Demand Units and irrigated area
Water rights for hydropower	1962-2007	32.18	Daily	Water diverted into bypass channel
Water leakage below Vallat dam	1968-2007	0.27	Daily	Filtrations of Vallat dam

* This location refers to the point where Arenós dam is now.
** Previously Head of the Department of Hydraulic Engineering and Environment, Universitat Politècnica de Valencia (Valencia, Spain).
*** (Pérez-Martín, 2005).

For each period, different calculations were performed, using the sources listed in **Table 5.2**, to estimate a monthly flow record from the available flow records and other information on the flow manipulations that were active:

- Before the 1956 image (pre-regulation), river flows were natural apart from water abstraction for irrigation. It was estimated that 50 % of the water demand in the traditionally irrigated lands was returned to the river (Paredes-Arquiola *et al.*, 2008).

- Between the 1956 and 1976 images (pre-regulation and hydropower operation), river flows were divided into two sub-periods. For 1956–1967 (pre-regulation), although the Cirat hydropower plant started to operate in 1962, the return of the bypass is upstream of both sites; thus irrigation abstraction remained the main human manipulation of river flows. From 1968 to 1976 (hydropower operation), the Vallat dam was in operation, with a maximum abstraction of over 12 m^3/s affecting the study sites.

- Between the 1976 and 1997 images (hydropower and dam operation), it was not possible to investigate flows during the period 1976-1979 because the river was managed for the construction of the dam, and there are no reliable data. From 1979, the Arenós dam came into operation, having a major effect on flows at the study sites in addition to the pre-existing hydropower and irrigation activities.

- Between the 1997 and 2007 images (hydropower and dam operation), flow manipulations continued as a result of operation of the same hydropower plants that affected the river in 1997 plus irrigation abstractions.

Eleven hydrological indices, which are relevant for the river ecosystem (Olden and Poff, 2003; Mathews and Richter, 2007; Monk *et al.*, 2007), were estimated from the resulting stream flow at each time period. The selected indices were a sub-set of those described by Belmar *et al.* (2011) to characterize Mediterranean rivers whilst avoiding redundancy. The selected indices describe typical or average conditions (mean annual flow – MADIS; median annual flow – Q50), variability (maximum annual discharge minus minimum annual discharge – RANGE; the coefficient of variation of mean annual flows – CVinter; the coefficient of variation of mean monthly flows – CVintra), high flows (maximum annual discharge divided by Q50 – AMAX/Q50; mean of the mean maximum monthly flows for all months – MH13; coefficient of variation in mean maximum monthly flows – CVH) and low flows (minimum annual flow divided by Q50 – AMIN/Q50; mean of the mean minimum monthly flows for all months – ML13; the percentage of months when the average flow was smaller or equal to 0.1 m^3/s – DL0.1). The last parameter represents the present minimum-flow conditions in the study area (approximate value of water leakage below Vallat dam).

5.4.2 Changes in land cover assessed from aerial images

Four sets of aerial images were identified to assess land cover at the study sites in 1956, 1976, 1997 and 2007. The 1956 and 1976 images were originally in black and white, and the 1997 and 2007 images were in colour. The July 1956 image came from the Centro Cartográfico y Fotográfico del Ejército del Aire (scale 1:10000; pixel size 0.7 m). The March 1976 image was obtained from the Confederación Hidrográfica del Júcar (scale 1:1500; pixel size 0.1 m). Images for November 1997, and August and September 2007 came from the Instituto Cartográfico Valenciano (scale 1:5000; pixel size 0.5 m). River discharges at the time of these surveys were 8.1, 0.1, 0.09 and 0.09 m^3/s, respectively.

The images were imported into ArcGIS™ version 9.3 (ESRI, Redlands, CA, USA, 2009). The 1976 imagery required geo-correction, and all images were registered to European Datum 1950 and UTM-Zone 30N. To perform a comparison among images that was unbiased by differences in their colour quality and spatial resolution, we converted the 1997 and 2007 images to greyscale and re-sampled the 1976, 1997 and 2007 images to match the 0.7-m resolution of the 1956 images.

The images were then interpreted to identify changes in land cover. The margins of each land cover patch across the entire river corridor were manually digitized, and an attribute table was created for the resulting polygons, including their code, perimeter (m) and area (m^2). Land cover types attributed to the polygons in the most recent images were checked in the field during spring 2010 over 70 % of the area of the study sites. This provided a means of verifying the attribution of land cover to the following seven classes: water (WA: open water), bare sediment (BS: cobbles, gravel and sand with vegetation cover lower than 5 %), herbs (HE: non-woody vegetation), sparse woody vegetation (SV: areas with woody herbs and small patchy shrubs and trees with a canopy cover less or equal to 40 %), dense woody vegetation (DV: areas with a dense woody canopy cover, typically higher than 60 %), cultivated (CU: farming land) and shade (SH: dark areas that could not be interpreted in the images). Because the aerial images were taken during different flow conditions, the active channel was defined as the union of water (WA) and bare sediment (BS) when the latter polygons were located immediately adjacent to the water, to permit analysis of changes in channel width and position (Takahashi and Nakamura, 2011). Pearson's chi-squared test was used to compare the resultant land cover maps, firstly comparing both sites within the same period and secondly comparing the maps for each site across periods.

The land cover information derived from the aerial images was analysed in two different ways to interpret changes in the structure and configuration of the riparian corridor. First, landscape metrics were extracted using the vector information describing land cover patch boundaries. The Patch Analyst Tool version 4 for ArcGIS™ version 9.3 (CNFER, Ontario, Canada, 2011) was used to quantify changes through time (Apan *et al.*, 2000) in a set of metrics (**Table 5.3**) that are thought to be meaningful when assessing landscape changes (Fernandes *et al.*, 2011). Second, the vector files were converted to 5-m resolution raster layers depicting the seven land cover types. The raster maps were overlaid chronologically, and a mask was employed to exclude areas affected by shade (SH) from the analysis.

Table 5.3. *Definitions of the landscape metrics extracted for land cover patches in the present study (adapted from McGarigal and Marks, 1994; McGarigal and Marks, 1995).*

Statistic name and abbreviation	**Description**
Patch density and size metrics	
Number of patches (NumP)	Total number of patches
Mean Patch Size (MPS)	Average size of patches (m^2)
Patch Size Standard Deviation (PSSD)	Standard deviation of patch areas
Patch Size Coefficient of Variance (PSCoV)	Coefficient of variance of patches
Edge metrics	
Total Edge (TE)	Total perimeter of patches (m)
Edge Density (ED)	Amount of edge relative to the landscape area (m/m^2)
Mean Patch Edge (MPE)	Average amount of edge per patch
Shape metrics	
Mean Shape Index (MSI)	Shape complexity. Equals one when all patches are circular and it increases with the patch shape irregularity
Mean Perimeter Area Ratio (MPAR)	Shape complexity. Sum of the perimeter/area ratio for all patches divided by number of patches
Mean Patch Fractal Dimension (MPFD)	Shape complexity. Approaches one for shapes with simple perimeters and two when shapes are more complex
Diversity metrics	
Shannon's Diversity Index (SDI)	Relative measure of patch diversity. Equals zero when there is only one patch in the landscape and increases as the number of patch types and/or proportional distribution of patch types increases
Shannon's Evenness Index (SEI)	Measure of distribution of area among patch types. Equals zero when there is no diversity (i.e. a single patch type) and one when the distribution of patch types becomes perfectly even

Three confusion matrices were obtained from these chronological overlays for each site, quantifying the detailed changes ('cell-by-cell comparison') between land cover types from one image to the next. The spatial distribution of agreement was summarized by the correctly classified instances (CCI), which is the total rate of pixels classified in the same category in both maps.

Additionally, the Map Comparison Kit version 3.2.2 (Research Institute for Knowledge Systems, The Netherlands, 2011) was used to confirm the temporal/spatial changes detected (Visser and de Nijs, 2006). Each pair of categorical raster maps was compared chronologically for each site on the basis of fuzzy set theory, where both fuzziness in category definition and fuzziness in location were considered (Hagen, 2003; Hagen-Zanker *et al.*, 2005).

Table 5.4. *Consistent category similarity matrix where each cell contains the grade of similarity between each pair of categories (land cover types) of the two maps in comparison. Values range between 0 (crisply distinct categories) and 1 (completely identical).*

	Category Similarity Matrix						
Map 1 \ Map 2	WA	BS	HE	SV	DV	CU	SH
WA	**1**	0	0	0	0	0	0
BS	0	**1**	0.9	0.6	0.3	0	0
HE	0	0.9	**1**	0.7	0.4	0	0
SV	0	0.6	0.7	**1**	0.5	0	0
DV	0	0.3	0.4	0.5	**1**	0	0
CU	0	0	0	0	0	**1**	0
SH	0	0	0	0	0	0	**1**

The fuzziness of categories was implemented by assigning to each cell a membership vector instead of a single category. Each element in the vector declares, with a value between 0 (crisply distinct) and 1 (completely identical), the degree of membership for one category (Hagen, 2002; van Vliet *et al.*, 2010). All this information is gathered in the category similarity matrix (**Table 5.4**), where similarity between categories decreases when distance from the diagonal increases. Only similarities between the types BS, HE, SV and DV were considered (according to the definitions stated earlier). The consistency of the resultant matrix was tested using the analytic hierarchy process developed by Saaty (1980).

The fuzziness of location considers that the fuzzy representation of a cell depends on the cell itself and, to a lesser extent, on the cells within a certain distance in its neighbourhood (Hagen, 2003). The extent to which the neighbouring cells influence the fuzzy calculation is represented by a distance decay function. In this study, a linear decay (cone shape, defined by slope = 0.5) and a radius of neighbourhood of two cells (equivalent to a 10-m radius) were considered as appropriate. Two global similarity indices were used to assess the similarity between the maps of fuzzy membership vectors: average similarity and fuzzy kappa. The average similarity is the fuzzy equivalent of the CCI (also known as 'fraction correct' or 'observed percentage of agreement'). The fuzzy kappa statistic is similar to the traditional Cohen's kappa (1960), i.e. the percentage of agreement between two maps is corrected for the fraction of agreement statistically expected if all cells were randomly relocated in both maps. Briefly, it corrects the percentage of agreement for the expected percentage of agreement based upon the histograms of the two maps.

5.4.3 Changes in land cover assessed from field survey

A detailed vegetation survey was conducted within a part of site 2 in 2007. The survey was conducted along transects across the riparian corridor perpendicular to the main flow direction and including the river channel (Garófano-Gómez *et al.*, 2008). All individual woody riparian plants were surveyed within each transect. The outer limits of the vertical projection of each plant or tree canopy on each transect were recorded using a Global Positioning System and total station (**Figure 5.2 a, b**). The canopy height and stem diameter at 50 cm above ground for shrub species and at 130 cm for tree species were recorded for every woody plant (**Figure 5.2 c**).

Core samples were obtained from the target woody riparian species across the study area and surroundings, but always within the middle course of the river, using pruning shears for small individuals and a Pressler drill for the large ones (**Figure 5.2 d**).

Figure 5.2. *Procedures applied during the vegetation survey: topographic measurements for recording the position of individual woody riparian plants within each transect using a total station (a) and a prism reflector (b), stem diameter measurements using a caliper (c) and core samples extraction using an increment borer or Pressler drill (d).*

These core samples were dried and sanded to increase the visibility of the annual growth rings, which were counted to estimate the age and to develop age–diameter relationships for each species (**Figure 5.3 a, b**). The target woody species and the number of core samples were as follows: rosemary willow (*Salix eleagnos* Scop.; N = 26), large grey willow (*Salix atrocinerea* Brot.;

N = 13), tamarisk (*Tamarix* spp.; N = 9), black poplar (*P. nigra* L.; N = 27), oleander (*Nerium oleander* L.; N = 24) and redoul (*Coriaria myrtifolia* L.; N = 11). The age–diameter relationships were used to estimate the age of all surveyed plants and thus the period (image) when they were established. The locations of the surveyed plants were overlaid on the aerial images to identify the land cover type within which they germinated and established.

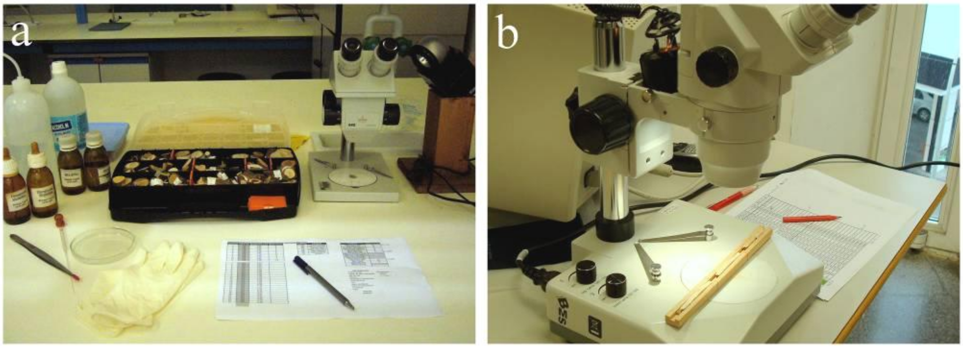


Figure 5.3*. Preparation of the sections (a) and core samples (b) and counting of the annual growth rings in order to estimate the age of the plants and develop age-diameter relationships for each species.*

5.5 RESULTS

5.5.1 Changes in river flow regime

Figure 5.4 summarizes trends in monthly flows within the four periods between the dates of the analysed images, indicating trends within sub-periods where there is a significant change in flow regulation activities. The pre-regulation periods (1940–1956 and 1957–1967) show an essentially natural flow regime (apart from water abstraction for irrigation that affects the entire 1940–2007 period), characterized by relatively high average flows that vary widely between and within months (**Figure 5.5**). Following the development of the Cirat dam from 1962 (**Figure 5.5**), peak flows were impacted but not the largest ones. Two large floods also occurred during this pre-regulation period (14 October 1957 and 24 October 1967). The magnitude of these two extraordinary events was not measured, but local newspapers (e.g. the ABC newspaper, http://hemeroteca.abc.es) reported that they destroyed several gauging stations and bridges, and so they probably caused severe disturbance to the riparian zone.

Following the closure of the Vallat dam in 1968, the flow regime was transformed (**Figure 5.4**), with almost all the flow diverted for hydropower production. From 1968, the riverbed was virtually dry for the majority of the time (Prof. J. Marco Segura, personal communication), with occasional higher flows occurring during exceptional storms or when the dam gates were opened to manipulate reservoir levels. As a result, since 1968, the median monthly flow and flow variability (indicated by the 10th and 90th percentiles) have been drastically reduced (**Figure 5.4**).

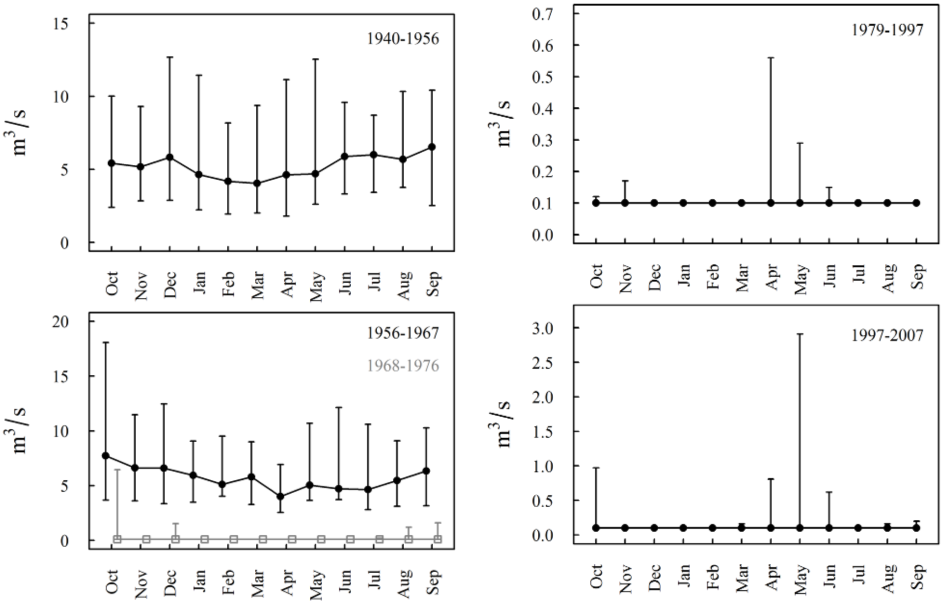


Figure 5.4. *The 90th and 10th percentiles (bars) and median of monthly flows within the designated months and periods. Note that the scale of the vertical axes varies between graphs to improve visualization and that different line colours (black, grey) and symbols (dots,*

squares) are used to depict data when the flow time series between images has been split into sub-periods.

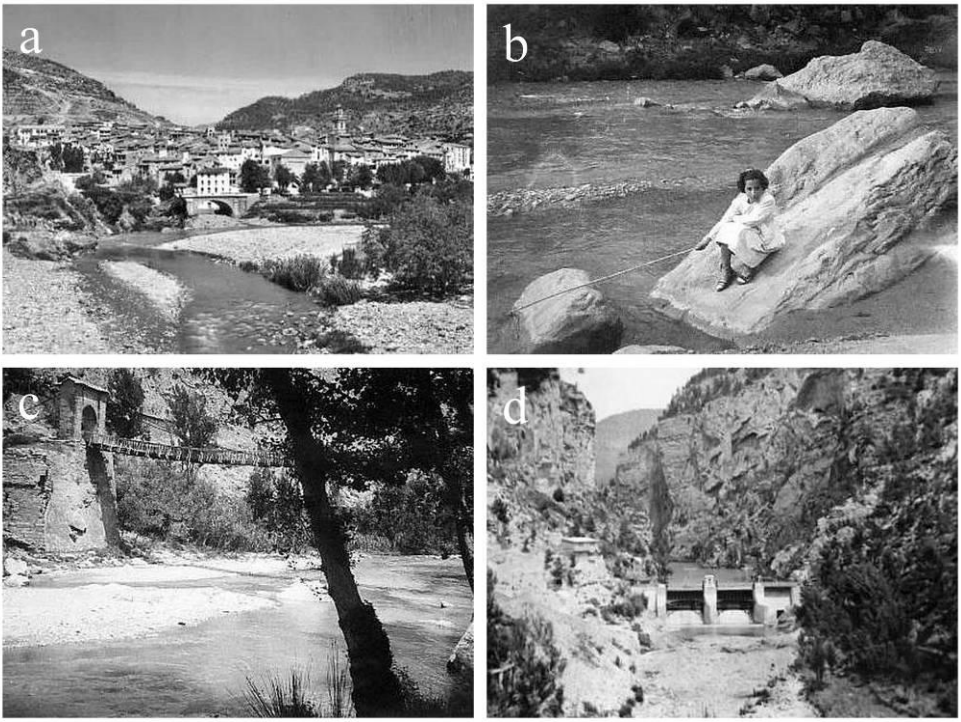


Figure 5.5. *Old pictures of the Mijares River. Pictures a (from Montanejos, upstream of our study area), b and c (from Toga, downstream of our study area) were taken in the 1950s and represent the pre-regulation period, characterized by relatively high average flows. Picture d represents the Cirat dam in the 1960s, as can be seen all the water is diverted and the riverbed is virtually dry downstream of this impoundment. Source: www.todocoleccion.net.*

These changes in flow are reflected in the values of the hydrological indices representing average-flow, high-flow and low-flow conditions during the four periods (**Table 5.5**). The mean annual flow (MADIS) shows a dramatic decrease, from around 6 m^3/s prior to 1968 to less than 0.5 m^3/s post-regulation, and the median (Q50) is even more severely affected, with a reduction of approximately 98 %. Flow variability is also greatly modified with a major reduction in the range (maximum minus minimum) of mean annual flows following dam closure (RANGE) apart from those in 1979–1997, during which large rain storms occurred in 1989–1990. There is also up to a tenfold increase in the coefficient of variation of flows between months (CVintra) and years (CVinter), reflecting the fact that the early years with a natural flow regime had a higher mean flow when compared with their (also higher) standard deviation. With respect to high flows, the average of maximum monthly flows (MH13) is approximately 13 m^3/s before 1968 and lower than 2 m^3/s post-regulation, with the exception once again of those in 1979–1997.

Table 5.5. *Hydrological indices for the analysed flow periods.*

	1940-1956	**1956-1967**	**1968-1976**	**1979-1997**	**1997-2007**
Average flow conditions					
MADIS	5.991	6.430	0.385	0.411	0.304
Q50	5.568	6.680	0.195	0.100	0.099
RANGE	8.901	6.762	0.882	4.075	0.736
CVintra	0.115	0.159	1.395	1.098	1.014
CVinter	0.414	0.322	0.957	2.359	0.996
High flow conditions					
AMAX/Q50	2.115	1.537	5.028	41.741	8.436
MH13	13.378	13.422	1.894	5.530	1.867
CVH	0.142	0.224	1.610	1.475	1.443
Low flow conditions					
AMIN/Q50	0.516	0.524	0.512	0.987	0.997
ML13	1.341	2.733	0.100	0.095	0.099
Duration of low flow conditions					
DL0.1 (%)	0	0	93	91	92

The variability across maximum monthly flows (CVH) has increased post-regulation because flows of an intermediate magnitude are very rare, and AMAX/Q50 shows a similar change due to the low post-regulation frequency of floods and the low values of the median annual flows. In relation to low-flow conditions are the following: (i) average minimum monthly flows have decreased dramatically, with ML13 not exceeding 0.1 m^3/s; (ii) the percentage of months with flow equal to or lower than 0.1 m^3/s (DL0.1) has exceeded 90 % since 1968; and (iii) AMIN/Q50 has remained approximately equal to 1 from 1979 (after the Arenós dam was built), indicating minimal differences between the minimum and median flows.

5.5.2 Changes in the areal extent and distribution of riparian land cover types

The areal extent and distribution of land cover types within the river corridor has changed dramatically during the last six decades (**Figure 5.6** and **Figure 5.7**). Before regulation (1956), the land cover types were present in similar proportions (**Figure 5.7**), the channel (water and bare sediment) was relatively wide and the most developed cover type (dense woody vegetation, DV) was often found set back from the margins of the active channel (**Figure 5.5** and **Figure 5.6**). Following regulation, there was an initial increase in bare sediment cover as the water area decreased (1976; **Figure 5.6**), and then vegetation started to colonize, with herbs (HE), followed by sparse shrubby vegetation (SV) and then by dense and more mature tree cover (DV), in turn encroaching across the river corridor (1976, 1997 and 2007; **Figure 5.6**) and leading to the virtual disappearance of bare sediment (BS) and early vegetation stages in 2007. The largest area of water (WA) is observed in the 1956 image with a dramatic decrease at both sites at all later dates (**Figure 5.7**). The highest percentage of bare sediment (BS) was found at both sites in 1976. Herbaceous cover (HE) is always more abundant at site 1 and, like BS, reached maximum cover in 1976. In contrast, dense vegetation (DV) achieved minimum cover in 1976, increasing greatly in cover in 1997 and 2007 and always showing a higher cover at site 1. Cultivated land (CU) extends across a sizeable area in 1956 but then reduces to 8 % or less in all subsequent images.

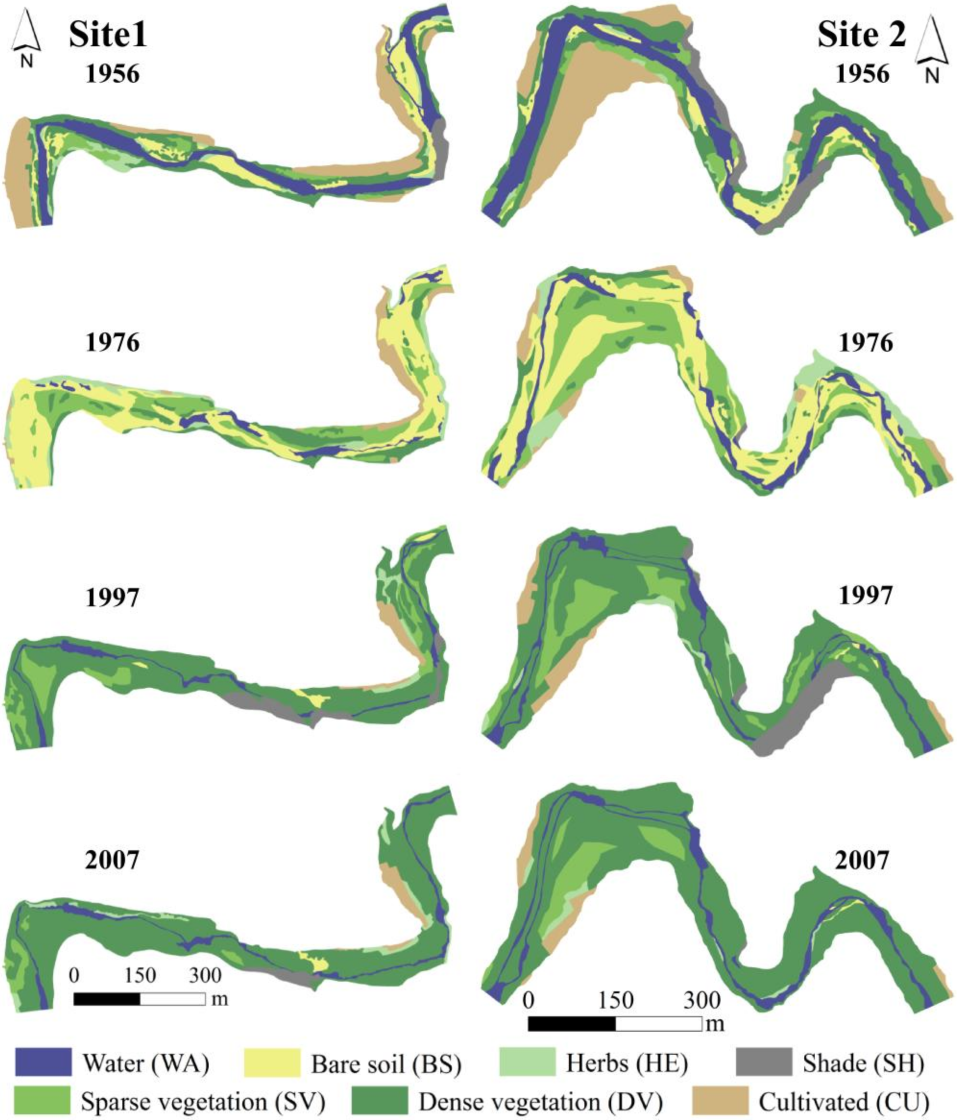


Figure 5.6. *Land cover maps for the pre-regulation (1956) and post-regulation periods (1976, 1997 and 2007) at both study sites.*

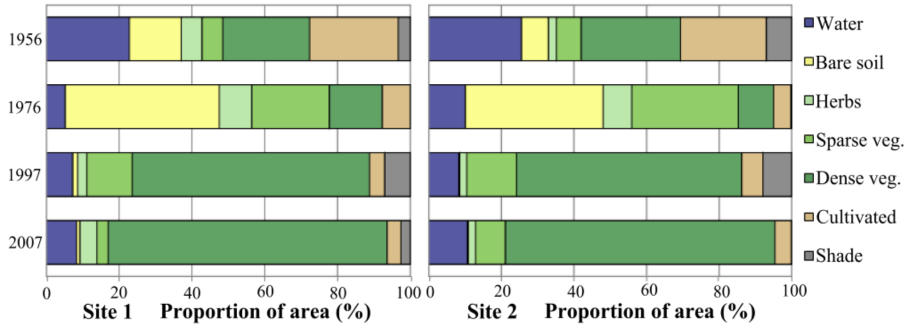


Figure 5.7. *Proportion of area covered by each land cover type in both study sites.*

Figure 5.8 illustrates the relative change in active channel area (WA plus adjacent BS) since 1956. There is a similar trend of reduction in channel area at both study sites to 1976, although the reduction at site 2 is smaller (93 %) than that at site 1 (73 %), with a larger reduction at both sites between 1976 and 1997 than between 1956 and 1976. Since 1997, there has been a small increase in active channel area at the two sites.

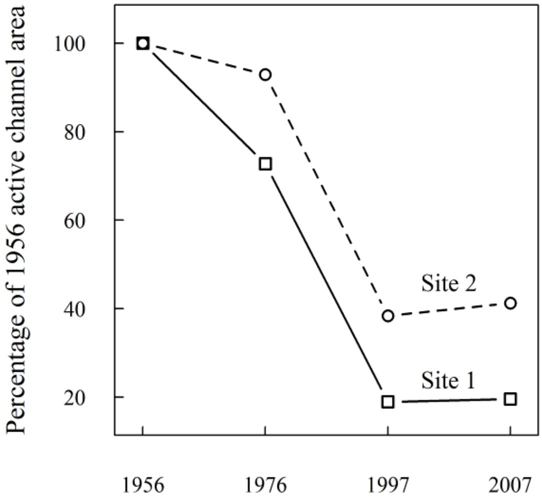


Figure 5.8. *Active channel area in 1956, 1976, 1997 and 2007, expressed as a percentage of that observed at both study sites in 1956.*

5.5.3 Riparian landscape structure

The riparian landscape structure, in terms of the number (**Table 5.6**) and size and shape (**Table 5.7**) of land cover patches, has changed greatly over the study period. The number of land cover patches has decreased by over 50 % between 1956 and 2007, with a particularly steep decrease between 1976 and 1997 (**Table 5.6**). In relation to the particular land cover types, WA showed the largest number of patches in 1976, along with SV, DV and CU, whereas BS and HE patches were most numerous in 1956 across the two study sites. The two sites show remarkably similar patch numbers in each of the four images. Pearson's chi-squared test performed with the number of patches by cover type (**Table 5.6**) as well as with their proportions indicated no significant differences between sites within each period, confirming their similar morphology and vegetation dynamics and likely representativeness of the middle course of the river. However, differences across periods for both sites were significant in all cases.

Table 5.6. *Number of patches by land cover type for the aerial images at both study sites (site 1, upstream; site 2, downstream). The codes of the land cover types are in the methods section and* ***Figure 5.6****.*

	Cover Type											
	WA		BS		HE		SV		DV		CU	
Date/Site	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
1956	2	2	15	14	16	12	8	11	25	27	5	6
1976	14	9	5	12	11	7	18	26	21	35	10	6
1997	4	3	3	3	3	6	7	12	14	11	2	3
2007	2	2	1	2	8	5	4	4	7	7	3	4

The calculated landscape metrics (**Table 5.7**) allow the complexity of land cover to be further explored between sites and periods. The metrics are remarkably similar at the two study sites at each date, although some small differences can be identified. However, there are notable changes in each metric between dates. Site 2 shows patches with a more complex shape than those in site 1, and patches before 1976 had higher shape complexity than those in 1997–2007 (mean perimeter area ratio, **Table 5.7**).

Table 5.7. *Landscape metrics for study sites 1 and 2 for the images from 1956, 1976, 1997 and 2007 (the metrics codes are explained in* ***Table 5.3****).*

	Date (Site)							
	1956(1)	1956(2)	1976(1)	1976(2)	1997(1)	1997(2)	2007(1)	2007(2)
Patch density and size metrics								
NumP	74	74	79	96	37	42	26	25
MPS	1830	1520	1710	1170	3660	2670	5210	4490
PSSD	3680	3590	4170	2680	7140	4520	8520	8910
PSCoV	201	237	243	230	195	169	164	199
Edge metrics								
TE	23000	17500	23600	22000	19000	17000	15800	14900
ED	0.170	0.156	0.174	0.196	0.140	0.156	0.117	0.133
MPE	310	237	298	229	513	415	609	595
Shape metrics								
MSI	2.197	1.986	2.135	1.997	2.506	2.337	2.677	2.583
MPAR	0.377	0.436	0.428	0.455	0.248	0.317	0.240	0.360
MPFD	1.650	1.676	1.653	1.684	1.583	1.614	1.581	1.648
Diversity metrics								
SDI	1.741	1.690	1.540	1.545	1.199	1.233	0.922	0.905
SEI	0.894	0.869	0.859	0.794	0.616	0.634	0.474	0.465

In general, mean patch size (**Table 5.7**) was larger at site 1 than at site 2, decreased across both sites by 13 % from 1956 to 1976 and then increased by 103 % from 1976 to 1997 and by 53 % from 1997 to 2007. The standard deviation of patch size increased from 1956 to 2007 at both sites, but there was no consistent trend in patch size coefficient of variance (**Table 5.7**).

In relation to the edge metrics, there was a reduction in total edge length (**Table 5.7**) from 1956 to 2007 with a slight increase in 1976, whereas mean patch edge length (**Table 5.7**) showed an opposite tendency, with higher values in 2007 than in 1956. Overall, the most recent images show larger (area and perimeter), less abundant and less complex patches, whereas the oldest images show smaller, more numerous and more complex patches.

In relation to patch shape, the mean shape index (**Table 5.7**) indicates circular polygons as its value approaches 1 and more complex, irregular polygons as its value increases. Mean shape index values are consistently higher for site 1 and are lowest for the 1956 and 1976 images. The mean patch fractal dimension (**Table 5.7**) achieved values in the range of 1–2 (the closer the value to 2, the more complex is the perimeter), with site 2 always showing higher values than site 1 and the 1956 and 1976 images showing higher values than the 1997 and 2007 images. Both patch diversity indices (**Table 5.7**) showed a similar decreasing trend through the study period. Although all the land cover types were present at all four dates (i.e. the same patch richness), the number of patches of all the types varied greatly between periods (**Table 5.6**), with more patches and also more similarly sized patches in the early images and with fewer patches dominated by a single cover type in later images (**Figure 5.6**, **Table 5.7**).

5.5.4 Land cover transitions

The confusion matrices (**Table 5.8**) show percentage transitions of pixels classified under each land cover between consecutive survey dates. The total percentages of pixels that remained under the same land cover (CCI index; in cell-by-cell comparisons) between 1956 and 1976, 1976 and 1997, and 1997 and 2007 were 29 %, 22 % and 76 %, respectively, at site 1 and 22 %, 21 % and 79 %, respectively, at site 2.

The fuzzy comparisons (**Figure 5.9**) indicated through the average similarity showed larger percentages of agreement between the maps than those percentages showed by the CCI index, in particular 47 %, 51 % and 86 % at site 1 and 38 %, 51 % and 87 % at site 2. Fuzzy kappa yielded values of 0.122, 0.146 and 0.548 for the chronological map comparisons at site 1 and 0.063, 0.160 and 0.615 at site 2; these results confirm that the more dramatic changes occurred in the first two transitions (1956–1976 and 1976–1997), and the largest overall similarity was obtained between the last two maps (1997 and 2007).

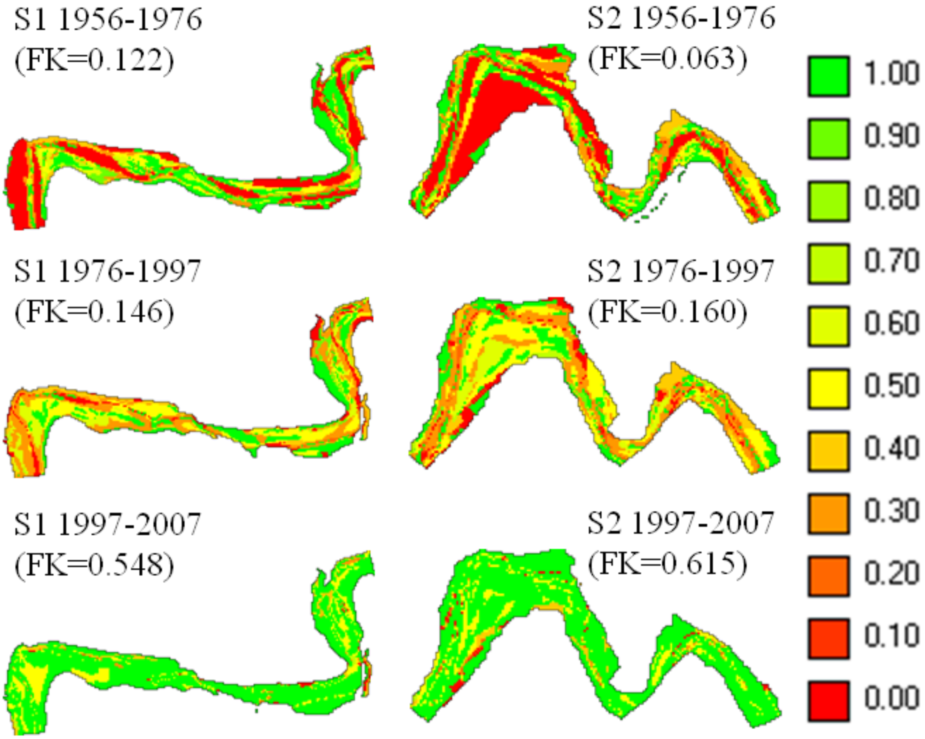


Figure 5.9. *Fuzzy similarity maps where the chronological map comparisons (1956-1976, 1976-1997 and 1997-2007) for each site are fuzzy set map comparisons, which take the fuzziness in category definition and fuzziness in location into account to express similarity of each cell in a value between 0 (fully distinct, in red colour) and 1 (fully identical, in green colour). The resulting fuzzy kappa statistic (FK) for each comparison is also shown.*

Table 5.8. *Confusion matrices of the raster maps for both study sites. For each comparison, data for the oldest map are presented in rows and the most recent in columns. For each pair of dates, the percentage of pixels that changed from one cover type (specified in rows) to another (specified in columns) is noted. The numbers in the diagonal (in bold) represent the percentage of pixels that remained unchanged for both dates.*

		Site 1						**Site 2**					
		1976 Image						1976 Image					
		WA	BS	HE	SV	DV	CU	WA	BS	HE	SV	DV	CU
Image 1956	WA	**16**	55	4	14	10	0	**17**	52	1	23	7	0
	BS	3	**52**	1	36	7	2	10	**52**	3	24	12	0
	HE	6	58	**3**	21	11	0	2	45	**13**	30	11	0
	SV	0	15	7	**49**	28	0	10	31	3	**51**	5	0
	DV	2	28	16	21	**30**	2	8	31	17	27	**17**	1
	CU	0	40	10	17	5	**28**	0	31	8	36	7	**18**

		1997 Image						1997 Image					
		WA	BS	HE	SV	DV	CU	WA	BS	HE	SV	DV	CU
Image 1976	WA	**50**	5	0	0	45	0	**46**	1	1	3	49	0
	BS	12	**0**	3	22	63	0	12	**0**	2	22	63	1
	HE	1	0	**0**	9	90	0	1	0	**1**	8	76	15
	SV	2	2	2	**14**	81	1	2	0	4	**16**	75	4
	DV	1	5	0	1	**93**	0	1	0	0	7	**90**	1
	CU	0	1	12	6	30	**51**	0	0	0	1	29	**70**

		2007 Image						2007 Image					
		WA	BS	HE	SV	DV	CU	WA	BS	HE	SV	DV	CU
Image 1997	WA	**66**	0	1	0	33	0	**65**	0	1	0	34	0
	BS	1	**43**	0	0	56	0	9	**36**	0	0	55	0
	HE	0	0	**49**	0	45	7	8	0	**0**	8	84	0
	SV	0	0	5	**12**	84	0	3	0	1	**47**	50	0
	DV	4	0	4	2	**90**	0	4	0	1	2	**91**	1
	CU	0	0	10	0	6	**84**	0	0	12	0	20	**68**

Notably stable land cover classes were BS and SV between 1956 and 1976 (during which around 50 % of pixels remained in these categories); DV, WA and CU between 1976 and 1997 (with around 90 % of pixels under DV, over 50 % under CU and around 50 % under WA remaining unchanged); and DV, WA and CU once more between 1997 and 2007 (with over 90 % under DV, over 60 % under WA and around 70–80 % under CU remaining unchanged). The most notable changes in land cover were from WA, HE and CU to BS between 1956 and 1976; from WA, BS, HE and SV to DV between 1976 and 1997; and from BS, HE and SV to DV between 1997 and 2007. Hence, DV (areas with a dense woody canopy cover) became an absorbing state at the scale of the river corridor following hydrological regulation (**Table 5.8**).

5.5.5 Contemporary data (transects)

When cross profiles of individual transects surveyed in 2007 are compared with the spatial distribution of the land cover classes along the same transects identified on the four aerial images for 1956, 1976, 1997 and 2007 (e.g. **Figure 5.10**), the accuracy of the image interpretation is confirmed, and the changes in land cover are clearly apparent. Lateral migration and narrowing of the active channel can be interpreted from these data, with implications for the space available for vegetation colonization. Evidence from the cross profiles confirm that lateral channel movements and narrowing mainly occurred between 1956 and 1976, since the channel position and width has stabilized. This stabilization has allowed the riparian corridor to be progressively colonized by vegetation, with dense woody vegetation dominating most of the riparian corridor by 2007.

The field surveys by transects illustrated that a variety of woody riparian species were concentrated along the margins of the river channel in 2007, including *S. eleagnos* (SE), *S. atrocinerea* (SA), *Tamarix* spp. (TA), *N. oleander* (NO), *P. nigra* (PN) and *C. myrtifolia* (CM).

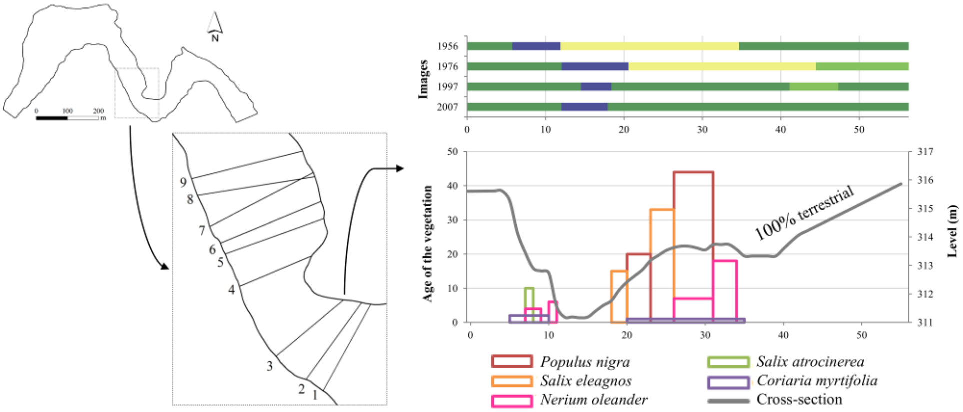


Figure 5.10. *The cross profile and plant species-age distribution recorded for transect 3, site 2 in 2007, in comparison with the distribution of land cover types estimated for the same cross section from the 1956, 1976, 1997 and 2007 images (cover classes presented in the same colours as in* ***Figure 5.6*** *and* ***Figure 5.7****).*

Linear age–diameter relationships with mainly high coefficients of determination (R^2) were obtained for the main species, as follows:

$$ageSE = 3.4599 * dSE + 0.5881 \ (R^2 = 0.6196)$$

$$ageSA = 1.8604 * dSA + 1.8145 \ (R^2 = 0.8495)$$

$$ageTA = 3.2664 * dTA - 0.281 \ (R^2 = 0.8193)$$

$$ageNO = 3.0878 * dNO + 0.0258 \ (R^2 = 0.9199)$$

$$agePN = 2.0849 * dPN + 1.832 \ (R^2 = 0.9812)$$

$$ageCM = 1.2104 * dCM + 0.5613 \ (R^2 = 0.868)$$

Figure 5.11 shows the sample size of these six species along the 2007 transects in relation to their age and the land cover type present in 1976 at the site where they were growing. From **Figure 5.11**, it is noticeable that most of the plants were less than 20 years old, with a few in the 20–30-year range and very few older than that. Indeed, 91 % of the plants recorded in the 2007 survey post-date the 1976 image.

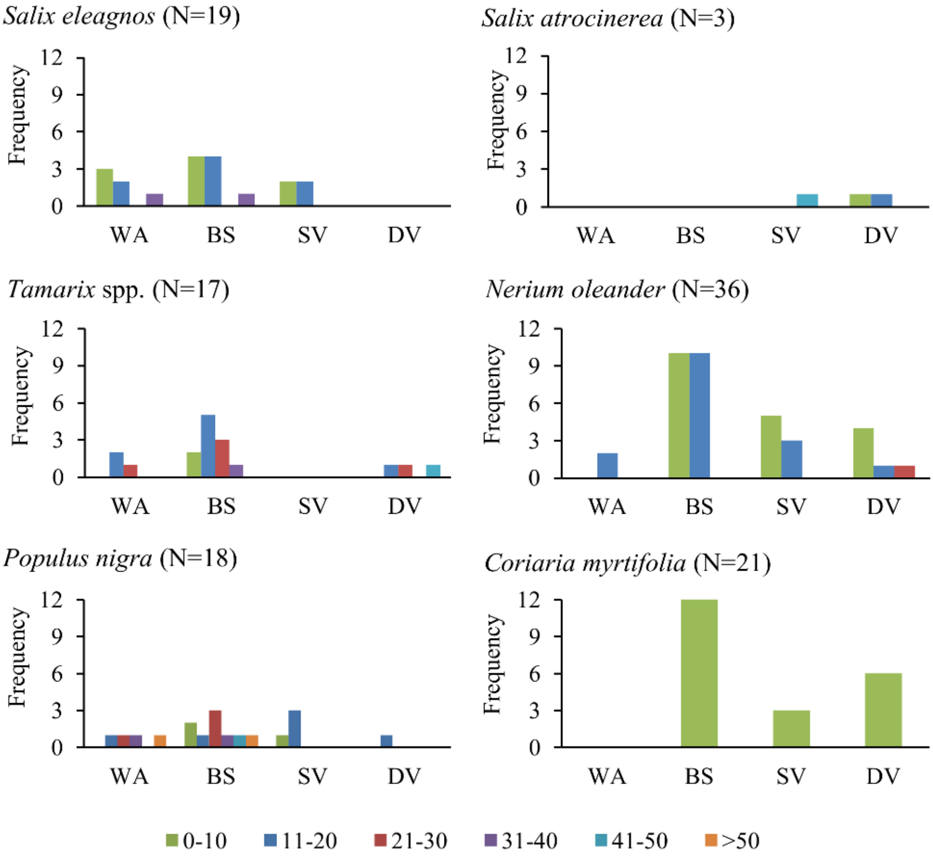


Figure 5.11. *Number of plants (frequency) of the different woody riparian species recorded in the field survey conducted in 2007 and overlaid upon the land cover types map from 1976. Each plant was assigned to an age interval of 10 years according to their age (i.e. a plant in the age interval 0–10 means that the plant was established in the period 1997–2007). Codes of land cover types refer to water (WA), bare soil (BS), sparse vegetation (SV) and dense vegetation (DV).*

Only ten of the individuals surveyed exceeded 30 years of age and were of only four species: *S. eleagnos* (located in WA and BS in 1976), *Tamarix* spp. (located in BS and DV in 1976), *P. nigra* (located in WA and BS in 1976) and *S. atrocinerea* (located in SV in 1976). Since 1976, the riparian corridor has been heavily colonized, with 54 % of plants colonizing areas identified as BS in 1976. The species of the younger individuals inventoried (i.e. those in the age range of 0–10 years) are largely *N. oleander, S. eleagnos* and *C. myrtifolia*, and these plants represented 43 % of all of the surveyed plants, possibly indicating a shift in the species composition to species with higher tolerance to water stress.

5.6 DISCUSSION

5.6.1 Use of historical information sources

In a retrospective study of this type, analysis has to be based on the historical sources that are available. This is a common situation in both river research and river management contexts, and so it is important for researchers to continue to explore both the potential and the limitations of different sources in relation to river research and management applications.

In the present study, we combined historical river flow data from a gauging site, modelled river flow estimates and information on different river flow manipulation activities. This fact constrained our reconstructed time series to a monthly resolution. This rather coarse temporal resolution is not ideal when investigating impacts on riparian systems because riparian vegetation is highly dependent on and responsive to shorter events, particularly droughts (Mahoney and Rood, 1998a; González *et al.*, 2012) and floods (Blondel and Aronson, 1999; Naiman *et al.*, 2008), which often form crucial elements in the definition of environmental flow regimes for riparian conservation (Rood *et al.*, 2003; Paredes-Arquiola *et al.*, 2011). However, only monthly data are available for many rivers and regions (Richter *et al.*, 2012), and in the present case, this was the highest resolution to which we felt able to construct an internally consistent flow series. This resulted from a number of factors, particularly the temporal resolution and uncertainty in the quality of historical gauged records used in flow reconstructions, which are derived from stations that no longer exist, and the variation in the quality/uncertainty between gauged sites that remain in operation. In any case, from the perspective of river management, we would like to remark that assessing hydrological indices at monthly time scale is coherent and valid with the application of Decision Support Systems (DSS) for water resources, which recently have demonstrated their capacity to optimize the flow regime considering the river habitat together with the legal and economical framework (Paredes-Arquiola *et al.*, 2011; Paredes-Arquiola *et al.*, *in review*). These DSS are essential tools for many water management authorities globally, thus providing wide future perspectives for the improvement of the riparian management at the basin scale.

Another constraint on our analysis was the resolution of the images that were used to explore land cover change. Early aerial images are usually monochrome, and their spatial resolution is usually rather coarse. Just as we felt it necessary to degrade the temporal resolution of the time series to a level whereby we were confident of an internally consistent data quality, we also degraded the imagery to that of the earliest, lowest-resolution images to ensure that any analytical results were not differentially affected by image resolution. This degradation also meant that it was essential for the images to be manually interpreted and digitized because their quality was insufficient for an automated procedure to generate useful outputs. Human interpretation is inevitably subjective, but to maintain consistency of interpretation, all images were interpreted and digitized by the same operator. Image degradation may also have introduced some errors in linking the land cover recorded from the field-surveyed transects to that on the images, although given the resolution of the degraded images (0.7 m), it is unlikely that any serious errors in our analysis can be attributed to this factor.

In the present study, combining different types of data has proven useful for reconstructing riparian changes. This type of integrated approach has been adopted in other studies using a wide variety of historical data sources. For example, at a local scale, within-patch forest metrics such as shifts in species composition, size class distribution, stem density (Shafroth *et al.*, 2002), canopy dieback and stem mortality (González *et al.*, 2010) can provide valuable information about vegetation response (at species level) to changing hydrologic conditions. At a landscape scale, information from herbariums (Crawford and Hoagland, 2009), archives, historical maps and land surveys (Johnson, 1994; Kondolf and Larson, 1995; Merritt and Cooper, 2000) can all contribute to reconstructions. Furthermore, there have been important advances in modelling that can aid reconstruction of the historical composition and development of riverine habitats under different pressures (Benjankar *et al.*, 2011; Hohensinner *et al.*, 2011; Benjankar *et al.*, 2012; Egger *et al.*, 2012).

5.6.2 Temporal and spatial changes: the utility of indices and metrics

Numerous indices have been proposed for summarizing ecologically relevant properties of the river flow regime (e.g. Olden and Poff, 2003; Mathews and Richter, 2007; Monk *et al.*, 2007; Belmar *et al.*, 2011), and we evaluated 11 of these during our study (**Table 5.5**). Although our estimates of many of these indices were probably adversely affected by the low (monthly) resolution of the river flow time series, all of the indices show distinct changes over six decades and clearly correspond to the timing as well as the impacts of dam closure on the flow regime of the Mijares River. Reductions in average, high and low flows are all clearly identified, giving confidence that the key changes have been recognized, even if changes in large flood events, which are so crucial to riparian disturbance, are not quantified. Furthermore, the clearest changes occur after 1976, corresponding with the closure of the Arenós dam, with some smaller changes evident in some indices during the 1968–1976 period, particularly in relation to inter-month and inter-annual flow variation and corresponding with the early operation of the Vallat dam.

As mentioned before, it is common to use monthly flow data in water resources management. Indices representing high flow conditions could be incorporated, like the rest of indices, in Decision Support Systems for Water

Management, so that in every river we could not only compare the values of the indices in post-regulation with those in pre-regulation but also compare the resultant indices with those from similar river systems. The pre-regulation data showed from the Mijares River in this study may represent a reference in this sense.

More innovatively, the vector and raster-based analyses of riparian zone land cover provide information that goes far beyond a simple description of stabilization and terrestrialization of the riparian zone. The analysis (**Table 5.7**) of changes in land cover patch density/number, size, edge length, shape and diversity provides a wealth of information from which the detailed dynamics of riparian adjustment to flow regime can be described and processes of adjustment can be inferred. Furthermore, the quality of the analysis of land cover is confirmed by the transect-based ground data, giving confidence in the outcomes of the analysis of landscape metrics.

Although in some cases subtle, the landscape metrics illustrate trends through the study period in patch number, size, shape and diversity and also in the relative number of patches under different cover types. Moreover, the most marked changes occur between the 1976 and 1997 images and so correspond with the closure of the Arenós dam. The combined use of fuzzy sets theory and a confusion matrix allowed the precise analysis of similarities between periods. Because vegetation often forms a mosaic, the classification of vegetation or land cover units into only one class is often difficult or erroneous (Muller *et al.*, 1998). Adopting a method for accuracy assessment based on the fuzzy set theory is particularly useful when comparing maps obtained by photo interpretation of geocorrected images, where some level of positional tolerance can be assumed (Power *et al.*, 2001; Foody, 2002; Wealands *et al.*, 2005) and also because adjacent categories have vague transitions in nature (Foody, 1996). A further benefit of using fuzzy sets theory is that it provides additional tools for analysing map similarity (Muller *et al.*, 1998). The fuzzy kappa gives more relevance to the spatio-temporal distribution of the landscape mosaic than other statistics because it is not based on a cell-by-cell comparison and it can capture qualitative similarities between two maps (Power *et al.*, 2001) because the categories of neighbouring cells are taken into account (Hagen, 2003; Hagen-Zanker *et al.*, 2005).

There are some practical differences between using aerial images and flow data to assess the ecosystem status. Nowadays, in the context of the Water Framework Directive (European Commission, 2000), a correct management has been established as crucial to monitor the ecological status and its changes. One of the differences between both approaches (images *versus* flow data) is their cost, since understanding the processes that are occurring in the riparian forest would require many images, on a regular basis, and a higher cost of processing information with respect to the analysis of flow series. From the point of view of the processes, images show a fixed picture that can reflect recent processes (e.g. a large flood, 1976 image) as well as the stability and lack of processes (e.g. 2007 image). However, the analysis of the flow regime integrates complete and detailed information, valid for a certain river length, and for a long period of time. In addition, as mentioned before, the use of flow indices allows us to compare the water management implemented by the different river basin authorities (for example, in management periods for 5-10 years) with the processes necessary for the maintenance and self-regeneration of the riparian forests. Studies like the one presented here are needed in order to relate riparian processes with flow indices and create background knowledge in this sense.

5.6.3 Interpreting the observed riparian dynamics

In general, our analysis reveals that there has been an increase in the cover and density of woody vegetation and a synchronous reduction in the complexity of the riparian corridor of the middle reaches of the Mijares River, which have accompanied a decrease in the magnitude and variability of river flows over the last 60 years (**Figure 5.4**). This adjustment has corresponded with a change from an essentially natural flow regime, which included occasional very large floods, prior to the hydropower developments in the 1960s and 1970s, to the current highly regulated regime.

In the 1956 image, the riparian corridor reflects the pre-hydropower, essentially unregulated flow regime. Land cover is varied, with the most even distribution of cover across the various classes amongst the analysed images and the most extensive area of cultivated land (**Figure 5.7**). The latter probably reflects the peak of agricultural intensity prior to rural depopulation in this part of the catchment and thus represents a human modification of the riparian zone at that time.

Between the 1956 and 1976 images (**Figure 5.7**), not only was there an implementation of the hydropower scheme, with the closure of the largest dam immediately prior to the 1976 image, but the riparian zone would also have been impacted by two very large floods in 1957 and 1967. Because these floods occurred at a time of rural depopulation, they may have been sufficient to drive cultivated land use out of the riparian corridor, accounting for the marked decrease in cultivated land cover by 1976 (**Figure 5.7**). In addition, the 1967 flood combined with the closure of the Arenós dam and the imposition of heavy flow regulation immediately before the date of the 1976 image explains the major increase in bare sediment land cover by 1976 (**Figure 5.6** and **Figure 5.7**). Indeed, the major transitions between land cover types were from water, herbs and cultivated land to bare sediment, with sizeable transitions from dense woody vegetation to bare sediment (**Table 5.8**). A major reduction in dense woody vegetation and an expansion in herbs and sparse woody vegetation between 1956 and 1976 (**Figure 5.7**) may also indicate the response of the riparian zone to large flood disturbances. However, the effects of these possible controlling mechanisms cannot be separated. They have combined to induce the land cover change between 1956 and 1976, which shows an increase in the number of land cover patches in virtually all land cover types (**Table 5.6**), a decrease in patch size, an increase in size variability and an increase in patch edge length between 1956 and 1976 (**Table 5.7**). Furthermore, the increased area of bare sediment and water land cover by 1976 appears to have provided the space for pioneer species to colonize, as evidenced by the large representation of riparian trees that are less than 30 years old located on these 1976 land cover types within the 2007 surveyed transects, particularly *P. nigra, S. eleagnos* and *Tamarix* spp. (**Figure 5.11**).

Between 1976 and 1997, the river flow regime was heavily regulated, and this appears to have allowed colonization of bare sediment and herb-covered areas within the riparian zone by woody vegetation and also the transition of much sparse woody cover to dense woody cover (**Table 5.8**). These transitions were accompanied by considerable simplification of the riparian vegetation structure, with a dramatic reduction in the number of land cover patches and the complexity of their shape, an increase in patch size and the domination of the riparian area by dense woody vegetation (**Figure 5.7**, **Table 5.6** and **Table 5.7**). This change in riparian cover and structure was accompanied by vegetation encroachment of the 1976 active river channel margins (**Figure 5.6**), a very major reduction in river channel width (**Figure 5.8**) and the appearance of some new species that were dated as less than 20 years old during the 2007 field survey, notably *N. oleander, S. eleagnos* and *C. myrtifolia* (**Figure 5.11**).

Between 1997 and 2007, the river flow regime continued to be heavily regulated, and the riparian vegetation structure continued to simplify, with the virtual disappearance of bare sediment cover and a further dramatic reduction of herb and sparse woody vegetation cover at the expense of dense woody vegetation cover (**Figure 5.7**). The 2007 field survey shows that within the dense woody vegetation patches, riparian tree species are confined to the active river channel margins with terrestrial woody species dominating the rest of the riparian corridor (**Figure 5.11**). The 2007 image shows a further reduction in the number of riparian patches (**Table 5.6**), a further increase in patch size and a reduction in patch shape complexity (**Table 5.7**). Although the structure of the riparian corridor vegetation continued to adjust during this period, active river channel narrowing stabilized and even showed a slight widening in comparison with that in the 1997 image.

As a general reference, in this kind of dynamic Mediterranean rivers, the percentage of change in natural conditions is around 70-80 % (site 1 and 2 obtained CCI values around 20-30 % in the first two periods: 1956-1976 and 1976-1997). On the other hand, percentage of change around 20-25 % would mean rivers in stable conditions (i.e. period 1997-2007). Regarding the active channel, which is related with the potential recruitment, its typical extent in natural conditions would be around 30-40 % (i.e. 30-40 % of the total area of the river corridor would be occupied by the active channel), with a percentage of change around 10 % depending on how active the river is. Similarly, in a non-dynamic situation (stable and flow-regulated conditions), the active channel area would be reduced to 10-20 % of the total river corridor area.

These observations show some similar trends to other studies. For example, Schmidt *et al.* (1995) found that changes were particularly noticeable in the first two decades after damming along the Snake River, USA. Harris *et al.* (1987) noted that after water diversion, the changes in the herb stratum tend to be the most pronounced, and Azami *et al.* (2004) observed that the reduced flood peaks below a dam led to the expansion of riparian forest area and its transition into later successional stages. Similar shifts were detected along the Green River, USA, by Merritt and Cooper (2000), 37 years after dam construction, indicating the eventual replacement of *Populus*-dominated riparian forest by drought-tolerant desertic shrubs and the enlargement of in-channel fluvial marshes. Similarly, many Mediterranean rivers have experienced a loss of riparian woodland, but few studies have attempted to spatially quantify that loss and its historical timing (Muller *et al.*, 2002). In the middle Ebro River, Spain, pioneer forests doubled their spatial extent after the intensification of the river regulation in the 1950s, but currently, they are characterized by declining, sparse stands of *P. nigra–Salix alba–Tamarix* spp., probably as a result of the increase in the frequency and duration of low water events (Ollero, 2010); and late-seral species are more frequent because their regeneration is not so dependent on recurrent fluvio-geomorphic events (González *et al.*, 2010).

On the Mijares River, our observations suggest that encroachment of dense woody vegetation across the riparian corridor is almost complete within 40 years of major dam closure and is associated with the persistent low-flow conditions and low-flow variability. These same factors have been identified as contributors to woodland expansion and encroachment in other rivers (e.g. Johnson, 1994; Huxman *et al.*, 2005; Santos, 2010; Magdaleno and Fernández, 2011). However, the composition of the vegetation within the Mijares riparian corridor appears to still be adjusting to some extent and is likely to take considerably longer to stabilize than our 60-year study period. This timescale conforms to that proposed by González *et al.* (2010) for the Ebro River, where the effects of regulation on vegetation structure are still not complete after 50 years. Indeed, in this context, Johnson (1992) suggested that almost two centuries would be required for riparian vegetation to reach a new post-dam steady state along the Missouri River. He attributed this to the longevity of *Populus* and *Salix* trees established before the regulation and their slow replacement by later successional species (Johnson, 1997). Although the *Populus* and *Salix* species observed along the Mijares River may be shorter lived than those along the Missouri River, they may be expected to survive for many more decades now that river channels dynamics are negligible, although they could decline rapidly depending on natural processes, such as the arrival of pathogens (Bastien *et al.*, 2009; González *et al.*, 2010) and invasive species, vertical bank erosions (Groeneveld and Griepentrog, 1985) and fires as well as human-induced processes, e.g. streambed mining and groundwater pumping.

Another aspect of the changes observed in riparian vegetation is the increase in non-native species at the study sites. There is a particular concern about the invasive cane or giant reed *A. donax* L. (Sanz Elorza *et al.*, 2004), declared by the International Union for Conservation of Nature as one of the most dangerous and harmful invasive alien plants worldwide (Bañares *et al.*, 2004). A similar invasion phenomenon has been observed in numerous studies where reduced recruitment of native riparian plants has followed severe flow regulation (Rood and Mahoney, 1990) and has been accompanied by the spread of non-native species (Johnson *et al.*, 1995; Merritt and Cooper, 2000; Stromberg, 2001; Shafroth *et al.*, 2002; Uowolo *et al.*, 2005; Richardson *et al.*, 2007). The invasive character of *A. donax* L. in the middle and low course of the Mijares River has already been recognized by the authorities (CHJ, 2008) and experimental actions are been carried out to control it (Jiménez, 2012; MARM, 2012). In the study area, it is not very abundant (yet), probably because its higher elevation and lower temperature (in comparison with the conditions in the low course where this species is more abundant), but the current stable river conditions and its high invasive potential may lead to a colonization of the complete riparian corridor in the short term.

5.6.4 Implications for management

Natural disturbances (such as fire and a flashy hydrological regime, typical of Mediterranean rivers), as well as site-specific human disturbances, control the structure of riparian vegetation (McIntyre and Hobbs, 1999; Johnson, 2000; Hughes *et al.*, 2001; Cooper *et al.*, 2006; Greet *et al.*, 2011). The life cycle of woody riparian vegetation depends on seasonal changes in water levels and extreme flow disturbances (Karrenberg *et al.*, 2002). If these changes are no longer present, the life cycle is interrupted, and riparian tree recruitment ceases or is dramatically reduced (Mahoney and Rood, 1998a; Braatne *et al.*, 2007). In particular, reduced flow disturbances lead to a reduction in the turnover of riparian habitats and thus reduced availability of moist bare sediment habitat for seed germination, and also an increase in hydric stress on established riparian trees located far from the channel margins (Harris *et al.*, 1987; Scott *et al.*, 1996; Auble and Scott, 1998; Kranjcec *et al.*, 1998; Nakamura and Shin, 2001). Furthermore, the changing vegetation structure can have important feedbacks, influencing future susceptibility of the riparian zone to disturbance (Shafroth *et al.*, 2002). For all of these reasons, flow regulation leads to a narrowing and ageing of the river margin riparian woodland and an encroachment of terrestrial species as has been observed along other semi-arid rivers (Huxman *et al.*, 2005; Santos, 2010).

Sustainable management of riparian ecosystems along regulated rivers requires the reinstatement of some of the natural elements of the flow regime (Richter and Richter, 2000; Hughes and Rood, 2003; Lite and Stromberg, 2005; Rood *et al.*, 2005; Merritt *et al.*, 2010). Furthermore, if river margin woodland is well established, even the reinstatement of significant high-flow events may not be sufficient to achieve riparian habitat turnover, and so some initial woodland management may be necessary.

In the case of Mijares River, the upper and middle course has been designated a site of community importance for its natural values because of the importance of the riparian habitats (Natura 2000 Networking Programme), but from our observations, these habitats are threatened if elements of the natural dynamism of the river are not restored. Thus, future dam management needs to respond to the expansion of the downstream riparian forest and its encroachment by terrestrial species, with the introduction of more natural disturbance elements into the flow regime. In addition, riparian changes have progressed sufficiently far for some tree felling as well as control of invading exotic species (e.g. *A. donax*) to be necessary, if the revised flow regime is to achieve rapid benefits for the riparian ecosystem.

Chapter 6

Conclusions and further research

6 CONCLUSIONS AND FURTHER RESEARCH

6.1 CONCLUSIONS

This thesis has been one of the first attempts in the Iberian Peninsula, and specifically in the Mediterranean region, to improve the poorly understood relationships between riparian vegetation and hydrogeomorphological factors at different spatial and temporal scales. It is expected that the conclusions derived from this thesis will serve to support the development of strategies for sustainable management of rivers and their riparian zones.

The thesis has covered the topic using different approaches. The chapters have been logically organized according to a hierarchy of scales. First, Chapter 2 has presented a study covering the physical conditions (morphology and soil variables) that determine the lateral distribution of the woody riparian species within the floodplain (i.e. a transversal-scale study conducted by cross-sections). In Chapter 3, the same information by transects from the two free-flowing reaches, along with drendrochronological estimations and flow time series, was used to define hydrological variables, riparian guilds and curves of hydrological response. Chapter 4 presented a longitudinal-scale study conducted by plots within study reaches, whose goal was to determine the main factors driving the spatial patterns of the floristic composition, riparian quality, instream habitat characteristics and heterogeneity on a hydrologically altered segment of the Serpis River. Finally, in Chapter 5 a spatiotemporal-scale study conducted at species and landscape level was developed in a segment of the middle course of the Mijares River, in order to interpret the long-term changes in the complexity of its riparian corridor due to flow regulation.

In the next pages, the conclusions of this thesis are detailed, divided into blocks, according to the organization of the document already explained.

Distribution patterns of woody riparian species in Mediterranean rivers. Comparison of regulated and unregulated sites

The comparison between abundance and cover values was established as an easy way to determine the structure of the riparian corridor within each site. The unregulated sites had a more heterogeneous shape and showed higher richness of species than the regulated sites. This could be explained because the former have a natural flow regime which is able to produce disturbances of intermediate intensity that promote a higher heterogeneity of physical conditions and therefore a mix of species with different requirements.

1. ***Definition of groups of species based on river morphology.*** The morphological variables produced more different rankings of species in free-flowing than in the regulated sites, due to the higher complexity (e.g. several channels) in natural sites. Furthermore, statistically significant differences were more evident in the free-flowing sites for both variables. In general, larger differences among species were detected in terms of elevation than in distance in both types of sites although the aggregation of species depended on the trimming percentage and significance level applied in each case. Distance is more affected by the irregularities of the cross-section and the specific location of the thalweg than the elevation, creating larger noise in the data set. The absence (or lower) differences showed by the distance in comparison with the elevation in regulated sites could have been caused by the severe reduction of fluvial disturbances that would have allowed the colonization of the entire transverse gradient. Even in this situation, elevation above thalweg was able to define a more gradual transition of species in the riparian zone. Moreover, according to our results, elevation above thalweg was a most robust measure than distance for a given species, because the ordination was more similar across sites in terms of elevation. Apart from this, distance and elevation performed similarly when the channel was single, but when it was more complex the elevation still continued performing well. For all these reasons, elevation above thalweg worked better and therefore the

conclusions from this variable are more transferable between rivers. Overall, our results agree with the general perspective of species zonation along rivers.

2. ***Woody riparian vegetation response to flow alteration.*** Although some exceptions occurred, no significant differences were detected between the specimens of a certain species in sites of the same kind, regulated or unregulated; however, they performed differently when the comparison involved sites with different flow regime. It was verified that certain species in regulated sites (i.e. along regulated rivers downstream from dams) are able to change the 'typical' positions that they occupy in unregulated sites, confirming a shift of species adapted to the new conditions. In our opinion, they can occupy closer positions to the river thalweg because of the lack of fluvial disturbances. In conclusion, riparian species have great potential as long-term bioindicators to flow regulation, since they are able to respond to the reduction of natural disturbances by means of a modification in their positional patterns.

3. ***Trends in soil properties along the lateral gradient.*** Contrary to our beliefs, the organic matter content was higher closer to the water's edge than in the transition floodplain–upland. This could be explained because the sites are relatively narrow. The slopes are very rocky with low organic matter content and the typical Mediterranean vegetation does not produce as much organic matter as the riparian species do.

Response curves and hydrological guilds of woody riparian species, oriented to water management in Mediterranean rivers

Coupling hydraulic models with geo-referenced survey of woody riparian species by transects, together with dendrochronological sampling, allowed us to obtain the time series of water elevations at which every single vegetation unit had been exposed during its entire lifetime. This basic information allowed us to define five hydrological response variables for key species and to assess their possible aggregation into hydrological guilds.

4. ***Riparian vegetation – flow response guilds.*** The presence of at least two potential guilds of hydrological response was consistent in both reaches. In relation to *inundation duration* and *inundation duration during growth period*, guilds could be defined at CRA, but not at MTE. However, although the values were always much larger at CRA than MTE, the ranking of species revealed was quite similar in both sites, *Salix purpurea* (SP) and *Salix alba* (SL) showed higher values for both variables than *Salix eleagnos* (SE) and *Populus nigra* (PN), and *Populus alba* (PA) at CRA. The variable *continuous inundation duration* showed higher overlap among species than the previous variables, and confirmed the differences in the flow regime between both sites, with shorter high-flow events in MTE than CRA. Only in the case of *elevation above base flow*, guilds were proposed for both reaches: [SP-SL] in low elevation and [PN-SE-PA] in high elevation at CRA and [SL] nearer the water, followed closely by [SP-SE] and [PN] in higher elevations at MTE. Taking all of this into consideration, three hydrological guilds were defined: 'highly tolerant to inundation', 'intermediate tolerant to inundation' and 'transitional between floodplain and terrestrial'.

5. ***Importance of the local physical conditions.*** Although both sites were located in the headwaters of their respective basins (in relatively narrow valleys) and belonged to the same ecotype (i.e. they shared similar physical characteristics), the sites differed in several aspects at large scale such as their flow regime (e.g. magnitude), stream order and catchment area, and also in aspects at local scale like the topography of the cross-sections, slope of the banks and soil texture. All these factors may have an important effect in the different response of the woody riparian species between both sites (in terms of average values of each hydrological variable).

6. ***Factors determining the accuracy of the response curves.*** Many factors play their role in the resultant curves, such as the flow time series and the quality of the hydrological reconstruction (if diversions and

tributaries occur between the closest gauging station and the site), quality of the hydraulic model (rating curves, calibration flows, etc.) and correct age determination (dependent on the quality of the growth functions).

Hydromorphological and floristic patterns along a regulated Mediterranean river: The Serpis River

This longitudinal-scale study provided a clear picture of the floristic composition, riparian and instream habitat quality and hydromorphological conditions in consecutive segments downstream of a large dam.

7. ***Longitudinal gradient of riparian and instream habitat quality.*** The changes in the instream habitat along the river were more prominent than the changes in the floristic composition, which varied more gradually. The sites with good and moderate riparian and habitat quality were located below the dam and in the middle course. The sites with the worst quality were near the river mouth and were characterised by an extensive presence of lateral structures and an artificial and highly variable flow regime (related to large autumnal floods and frequent human-induced periods of zero flow). These hydromorphological alterations have resulted in the impoverishment of vegetation, with a stronger presence of annual herbs and exotic species in the lower course than in the rest of the river course.
8. ***Correlation between floristic composition and QBR components.*** The total QBR score and the vegetation cover quality (QBR3) were the components most correlated with the floristic composition. The highest riparian quality was found at those sites associated with a high slope and low intervention in the surrounding area, favouring a connection among aquatic-riparian-terrestrial vegetation.
9. ***Correlation between instream habitat characteristics and IHF components.*** The total IHF score, riffle embeddedness or sedimentation in pools (IHF1), riffle frequency (IHF2) and the flow velocity/depth regime (IHF4) were the IHF components most correlated with the

instream habitat quality characteristics. The highest instream habitat quality was found at those sites associated with high substrate (such as boulders), moderate and dense shading, presence of mesohabitats associated with fast flow (currents, glides, runs and riffles) and large values of mean and maximum river depth.

10. ***Monitoring standards in areas with a geomorphological control.*** Physical constraints (presence of a gorge) have protected sites in the Serpis River from severe human impacts, resulting in good ecological quality, despite hydrological alteration. This area could be potentially reclassified into a different ecotype, because regular monitoring may use incorrect references for index scores, and naturally high scores could be confused with recovery from hydrological alteration or other pressures. Besides, monitoring of riparian status should be dependent on a geomorphological reference. Instead of using fixed characterisations of some indices, it could be useful to employ an open characterisation for certain riparian attributes and then measure the deviation of those riparian attributes from the geomorphological reference condition. This system would be simpler to apply and could be more transferable across regions in comparison with the variety of indices currently in use.

11. ***Necessity of implementing an environmental flow regime to improve the hydromorphological quality.*** This measure would provide lateral connectivity for the riparian vegetation with the main channel and longitudinal connectivity for fish fauna along the river. Especially important would be providing periodic high-flows events and maintaining minimum flows during the summer season. Another recommendable measure would be to provide the river with more space (incorporating abandoned agricultural plots into its banks) and lateral mobility (removing some lateral structures).

Six decades of changes in the riparian corridor of a Mediterranean River: A synthetic analysis based on historical data sources

River flow data from different sources were used to reconstruct a flow time series to a monthly resolution for a river segment in the middle Mijares River. Then, hydrological indices were obtained from the resultant time series to summarize relevant properties of the river flow regime. Complementary, a temporal set of aerial images with different attributes and from different sources were standardized to make consistent their quality and so that interpret the land cover changes through the definition of landscape metrics.

12. ***Combination of spatial analysis techniques gave confidence to the results.*** The analysis of changes in land cover patch density/number, size, edge length, shape and diversity provided a wealth of information from which the detailed dynamics of riparian adjustment to flow regime could be described and processes of adjustment could be inferred. The vector and raster-based analyses provided information that went far beyond a simple description of stabilization and terrestrialization of the riparian zone. Furthermore, the quality of those analyses was confirmed by the transect-based ground data, giving confidence in the outcomes of the analysis of landscape metrics.

13. ***The most marked changes in the riparian corridor corresponded with the closure of the Arenós dam after 1976.*** Reductions in average, high and low flows were all clearly identified. Smaller changes were also evident in some indices during the 1968–1976 period, particularly in relation to inter-month and inter-annual flow variation and corresponding with the early operation of the Vallat dam. The riparian corridor consisting of an even distribution of the different cover types with high complexity in the pre-regulation situation, changed to bare sediment and then it was colonized by vegetation. This last transition has been accompanied by considerable simplification of the structure, with a reduction in the

number of patches and the complexity of their shape, an increase in patch size and the domination by dense woody vegetation.

14. ***Woodland expansion, encroachment and shift of species.*** The expansion and encroachment of woody vegetation (increase in density and cover) across the riparian corridor, along with a synchronous reduction in the vegetation complexity, is almost complete within 40 years of major dam closure and is associated with the persistent low-flow conditions and low-flow variability. The analysis based on transects revealed the narrowing and ageing of the river margin riparian woodland as well as the encroachment of terrestrial species within the riparian corridor. In addition, enlargement of in-channel fluvial marshes and increase of non-native species (like the invasive cane *Arundo donax* L.) was also detected at the study sites and surroundings.

15. ***Restoration of the natural river dynamisms.*** The riparian habitats protected by the Natura 2000 Networking Programme at the Mijares River are threatened if elements of the natural dynamism of the river are not restored. More natural disturbance elements (such as significant high-flow events and release of the sediments retained in the dams) should be introduced into the flow regime in order to achieve riparian habitat turnover. Besides, some initial woodland management may be necessary like selective tree cutting as well as control of invading exotic species.

6.2 FURTHER RESEARCH

During the process of this thesis, in the collaboration within different projects, and during research stays in research institutions out of the Universitat Politècnica de València, I have identified several topics where I consider that further research would be interesting for the next future, based on the advances explained in this PhD thesis. In summary they can be explained as follows:

- **Hydrobiogeomorphology.** To explore new methods and variables to study the interaction between riparian vegetation and hydrogeomorphology in Mediterranean rivers (Corenblit *et al.*, 2010).

- **Riparian ecology.** To study the factors affecting the dynamics of the riparian communities focusing on the temporal evolution of the vegetation through succession and retrogression processes and its application to dynamic modelling (Egger *et al.*, *in press;* García-Arias *et al.*, *in press*).

- **Habitat suitability modelling**. To explore other statistical methods (e.g. techniques based on fuzzy logic) to develop curves of hydrological response for woody riparian species and evaluate which of the hydrological variables explain the presence of each species best. Furthermore, as some studies have shown that pioneer species increase their flooding tolerance with age (Siebel and Bouwma, 1998), this would support the idea of separating individuals according to their age to create response curves.

- **Ecohydrology.** To continue further exploring the aggregation of species into riparian guilds in other rivers and correlate them with physiological attributes (Merritt *et al.*, 2010; Bejarano *et al.*, 2012a) due to the importance of considering the riparian forest in the water management.

- **Flood analysis.** To apply dendrochronological techniques to reconstruct past flood events in Mediterranean rivers, especially high-magnitude floods, which are important to verify flow regime reconstructions, and in general highly relevant in riparian ecology (Zielonka *et al.*, 2008; Ballesteros Cánovas *et al.*, 2011; Génova *et al.*, 2011).

- **Riparian condition assessment.** To develop and test an ecological metric based on the positions of certain woody riparian species, assessing the level of regulation of a given river segment in terms of the possible deviation from a 'reference condition' (Pont *et al.*, 2006).

Chapter 7

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